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Selected Geotechnical Properties of a Calibration Test

Buried Explosives Against Shallow Targets

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This report characterizes the geotechnical properties of a grout material used as a testbed for the Defense Nuclear Agency sponsored project, Buried Explosives Against Shallow Water Targets (BEAST), a calibration test. The BEAST research program was designed to model the behavior of explosion shock waves in gassy littoral marine sediments and the effects on a ship passing over an exploding mine buried in such sediments. The grout material was chosen as a "synthetic sediment" which would simulate a natural, gassy, littoral marine sediment deposit.

The grout was core-sampled and analyzed for mass physical and mechanical properties both prior to and after an explosive charge was detonated within the testbed grout material.

The resultant physical properties determined from the grout were compared to those same properties derived from natural marine sediments. Significant similarities and differences were noted for future work with the grout for testbed purposes. In summary, shear strength data appear to be reasonably good measurements; physical property measurements including water content, wet bulk density, dry bulk density, and textural analysis (gross grain size) appear to be reasonable and of high quality. The greatest concern appears to be the inability to obtain reliable grain density measurements and, thus, confidence in the derivative physical property determinations (percent gas, percent saturation, porosity, and void ratio). The differences and variability in the grain densities significantly affects volumetric measurements of gas content, percent saturation, porosity, and void ratio.

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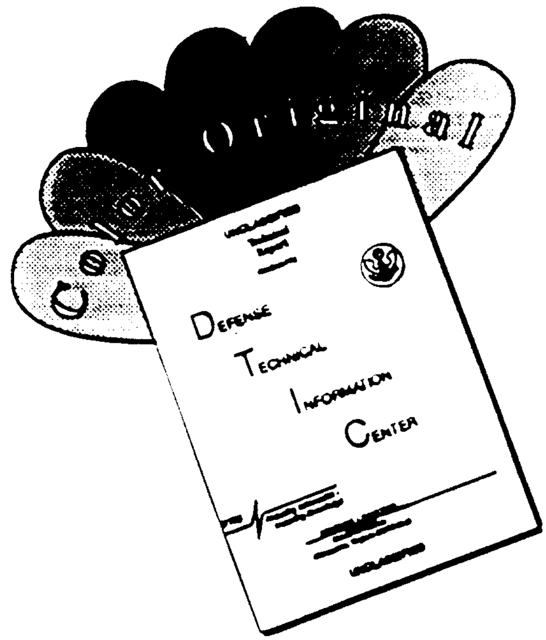

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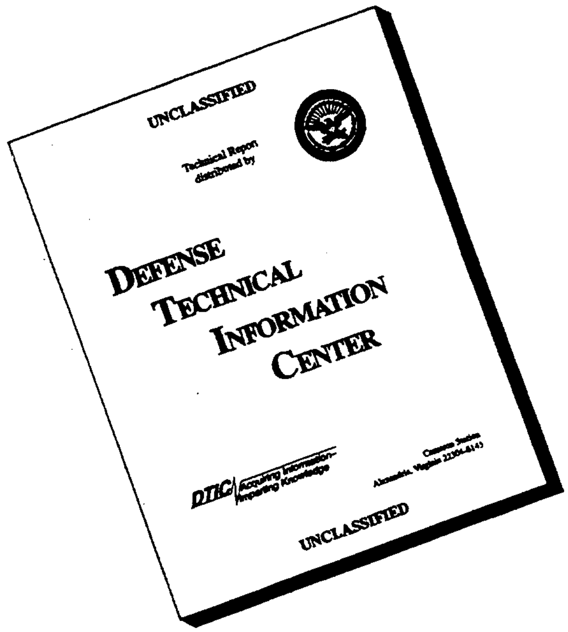

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BEAST CALIBRATION TEST

INTRODUCTION

As part of a research program designed to understand and model the behavior of explosion shock waves in gassy littoral marine sediments and the effects on a ship passing over an exploding mine buried in such sediment, the Defense Nuclear Agency sponsored the Buried Explosives Against Shallow Water Targets (BEAST) project. Since such a program is of necessity extremely ambitious, the BEAST technical staff proposed to begin by creating a set of "simple" experimental data based on an artificial sediment whose various parameters were precisely known and controlled. This would provide the modelers a well-controlled, reasonably tractable problem, as opposed to immediately attempting to handle the complexities inherent in the natural marine sediments. The BEAST Calibration Test also establishes benchmarks in anticipation of experiments involving natural sediments.

From the standpoint of the technical staff dealing with the testbed materials aspect of the experiment, the immediate objectives of the BEAST Calibration Test are threefold; a long-term fourth objective is implicit:

(1) Select a material suitable for the testbed.

(2) After the testbed is ready but before the charge is fired, core-sample the testbed and measure the physical and mechanical properties and behavior of the testbed material to characterize the material in situ.

(3) After the explosive charge is fired, repeat step (2) to determine effects of the shock wave on the material.

(4) Evaluate problems encountered and solve them, if possible.

To initiate the first of these objectives, scientists and engineers from the DNA, the Naval Surface Warfare Center-White Oak (NSWC-WO), Wiedlinger Associates, the U.S. Army Corps of Engineers' Waterways Experiment Station (WES), Research & Development Associates/LOGICON, Science Applications International Corporation,

and the Naval Research Laboratory (NRL) conferred to identify a material that would satisfactorily simulate an "ideal" widely occurring littoral marine seafloor sediment. NRL provided detailed technical data on the geotechnical properties of real-world shallow-water sediments to be used as a yardstick in the selection of the simulated testbed material (Bennett et al., 1970, 1977, 1980, 1995, Lambert et al., 1981). With this guidance, and following their own experience with grouts used to plug tunnels involved in underground nuclear explosions, etc., WES formulated, mixed, and put into place a test pond at Big Black River Test Site, a 6-ft. thick bed of synthetic sediment consisting of a water slurry of fly ash, Aquagel polymer, and Portland cement. The configuration of the testbed and the placement of sensors and gauges within it followed recommendations of the BEAST technical staff and were designed to accommodate the requirements of the modelers to the extent allowed by funding and implementation considerations.

To achieve the second and third objectives, WES and NRL collaborated to core-sample and test the grout material both before and after the testbed was subjected to a shock wave created by an explosive charge. In both cases, the cores were collected using NRL's standard marine geotechnical equipment. Preliminary analyses of the core samples was conducted at the WES Structures Laboratory immediately after the cores were taken (April 1995). Subsequently, at the NRL facilities, NRL measured additional mass physical, mechanical, and index properties of the grout. WES Structures Laboratory also performed tests on core samples to determine the grout's final composition, as well as various mechanical properties. For detailed information regarding the experiment design, the results of the WES experiments with grout, and their laboratory tests on the testbed and its material see the Quick Look Report for the BEAST Calibration Test (Ford and Phillips, May 1995). Also see additional reports presented at the June, 1995 meeting, NSWC-WO, Ford (1995), Goertner (1995), Phillips (1995), Sandler (1995), Bennett et al. (1995).

The fourth objective is a challenging aspect of research. In an experiment of the type conducted in this project, it can be confidently predicted that problems, both minor and serious, will emerge for both the experimentalists and, perhaps most of all, the modelers. The flooding of the Big Black Test Site, preventing access to the test site for post-TZ sampling, was one example. This kind of problem is beyond control or prediction. The presence of hollow glass beads in the fly ash used in the grout is a second example. It is also an example of the way a seemingly very small factor can have significant effects.

THE TESTBED

Testbed Composition

As noted, the first objective was to select a material that would simulate a representative shallow-water marine sedimentary deposit. Drawing on the results of an enormous amount of work by the academic researchers and the Navy research and survey communities, NRL has amassed a compendium of technical data on the geotechnical properties of shallow-water sediments in numerous locations around the world. While this compendium shows that one of the most conspicuous traits of such sediments is their great variability, they do have a number of highly predictable and interrelated characteristics. NRL used a composite of those characteristics to provide guidelines for the selection of a simulated sediment for the testbed material. From this point, WES used a straightforward rationale to select the grout as the material for the BEAST testbed. Grout can be prepared to simulate a soft mud, and since the composition of the grout can be precisely controlled, it was believed that the geotechnical properties of the testbed could be closely predetermined. This approach capitalizes on the Corps of Engineers' vast experience with grouts in a variety of scenarios, and has the added attractions of using readily available, relatively economical, and easily handled materials.

The grout mixture (ENM-6) used in the experiment was provided by the WES (Bruce Phillips) and is reported in "mixtures for 1.0 cu. ft. batch, lbs". The grout consisted of admixtures of the following: cement (Portland Type 1), fly ash (Class C), Aquagel, and water. The proportions of these materials mixed for 1.0 cu. ft. batch, lbs was: 2.6 for the cement, 38.0 for the fly ash, 3.8 for the aquagel, and 45.7 for water. The resulting grout had a wet bulk density of 1.44 Mg/m^3 as reported by the WES. Details are in Ford and Phillips (1995).

A major component of the grout is fly ash, and while the properties of fly ash can vary rather widely depending on the processes involved in its derivation and capture, the fly ash used in the testbed grout is exceptionally uniform, with highly consistent physical properties. The characteristics of fly ash are discussed in more detail in Appendix A.

TESTBED CORE SAMPLING

NRL's testbed coring system consisted of a 10-ft plastic pipe (3.0" I.D., 3.5" O.D.) with an approximately 500lb lead-weighted coring head at its top and a core cutter and core catcher attached to its bottom. A sheet of plastic taped around the core catcher inside the barrel minimized water loss and potential desiccation of the sample. A crane provided and operated by WES maneuvered the coring device into precisely surveyed positions over the testbed (Fig. 1). The positions were carefully chosen to provide representative samples of material while avoiding prelocated sensors and gauges.

Core Locations

Shot location (Ground Zero: GZ) and time (Time Zero: TZ) for the 8-lb explosive charge provides references for range and time in the experiment. Ranges were 10 ft, 12.5 ft, and 15 ft from GZ. Time is reckoned pre-shot (pre-TZ) and post-shot (post-TZ). NRL collected 5 pre-shot and 6 post-shot cores, for a total of 11 cores. A pair of pre-TZ cores came from each of the 10-ft and 15-ft ranges and one from the 12.5-ft range. Post-TZ, all three ranges were cored twice. Figure 1 shows the core locations.

Coring Schedule

Pre-TZ coring occurred on April 18, 1995, preceeding TZ by about 2 days. Post-TZ coring was complicated by the flooding of the test area immediately following TZ, as Big Black River overspread its banks in response to some typical Mississippi inches-per-hour rains. Post-TZ coring took place on April 26, as receding waters allowed access to Big Black Facility.

LABORATORY CORE PROCESSING

Immediately after the pre-TZ coring operation was completed, the cores were carefully transported in an upright position to the WES Structures Laboratory. There, NRL scientists extruded the cores, observed and recorded physical descriptions of the material, sampled the cores, and performed several property measurements. Various cores and core splits were retained by WES for their own testing. After initial

processing at WES was completed, NRL transported their cores to their Stennis laboratory for further processing.

Geotechnical analyses were conducted on specific intervals in cores taken at the Big Black test site for the BEAST Calibration Test.

The geotechnical laboratory procedures and principles are presented and discussed in Appendix B to allow the reader a general understanding of the techniques used to obtain the data. References are listed to provide the additional resources for further information.

Sediment Core Descriptions

The visual observations of the pre-TZ cores made at the WES Structures Laboratory represent a literal "first look" at the in situ testbed material.

The grout cores from the BEAST Calibration Test were all consistently light tan in color (10YR6/3, Munsell Soil Color Chart) and felt somewhat sticky and plastic. The grout appeared to show water mobility upon physically shocking a sample in one's hand, which indicates a nonplastic soil (Lambe, 1951). The texture or size of the particles in the material both visually and to the touch appear to be consistent from core to core with small variations in grittiness indicating some variability in amount of sand and silt-sized particles mixed within the grout. Cores taken post-TZ appeared to have a more sandy character (at the bottom of the cores) as indicated in the field when the cores were taken and subsequently capped. This sandy material recovered in the bottoms of the cores may have resulted in displacement of the grout from the explosive event and the sampling of the underlying sand bed used in construction of the test bed (Ford, M. and B. Phillips, 1995). The apparent water mobility, i.e., permeability and low affinity of the grout material for adsorbed water (compared with natural clay minerals), and the apparent nature of the material to "set up" within short time intervals are unusual as compared with typical marine sediments, although some marine sediments have a thixotropic nature.

The various laboratory tests and measurements performed by NRL are listed:

(I) NRL Measurements at WES Structures Laboratory

At the WES Structures Laboratory, NRL performed several physical property measurements. These included:

(1) water content
(2) volumetric wet bulk density
(3) shear strength
(4) remolded shear strength

The WES Structures Laboratory also performed a series of measurements on splits of the samples; see Ford and Phillips (1995).

(II) Subsequent NRL Measurements at SSC Laboratory

At their facilities at Stennis, the NRL Geotechniques Team continued analysis of the samples. This included:

(5) calibration of the volumetric tubes
(6) pore water density
(7) average grain density analyses
(8) scanning and optical microscopy examinations and analyses
(9) grain size distribution
(10) remolded shear strength vs. time

(III) Derived Physical Properties

Using values obtained during the measurements, NRL calculated the following:
(11) wet bulk density
(12) void ratio
(13) porosity
(14) percent (water) saturation of the sample pore spaces
(15) percent gas

Due to lack of cohesion/plasticity of the material, attempts to obtain Atterberg limits were unsuccessful (unlike typical marine sediments).

PHYSICAL PROPERTY MEASUREMENTS

The following sections list the results of the laboratory tests and measurements performed by NRL and gives examples of similar quantities from natural marine sediments for comparison.

(I) NRL Measurements at WES Structures Laboratory

(1) Water Content (*w*)

Water content is measured by weighing a sample of material, drying it for 24 hours in a 105°C oven, and reweighing.

The average value obtained from all cores, pre-TZ and post-TZ, was 100.8% (see Table 1), with mean values of 100.2% (Table 2), pre-TZ and 101.3% (Table 3) post-TZ.

Mean grout value	100.8%
Chesapeake Bay, clayey silt	126.3%
Western North Atlantic continental slope sediments	88.0%

(2) Volumetric Tube Sampling

Volumetric tube sampling is done by filling precision machined and measured (volume and weight) stainless steel tubes with sediment and performing various volume and weight dependent tests on it. These are used to determine wet bulk density, void ratio, porosity, percent saturation, and gas content. Specifically, the numbered tubes were carefully filled and leveled, weighed, dried for 24 hours in a 105°C oven, and reweighed with the dry sediment. The average precision of the tube volumes is 0.01 cc with maximum values of 0.04 cc (Bennett et al., 1995).

(3) Shear Strength

For the grout, mean undrained shear strength from all the pre-TZ cores was 5.2 kPa (Table 2). For all the post-TZ cores it was 7.8 kPa (Table 3). Overall mean for all cores, pre-TZ and post-TZ, was 6.8 kPa (Table 1).

Shear strengths of various sediments are:

Mean shear strength of the grout is:	6.8 kPa
Chesapeake Bay, clayey silt	3.8 kPa
Western North Atlantic continental slope sediments	8.3 kPa

(4) Remolded Shear Strength

Remolded shear strength is the shear strength of the sediment after it has been worked and remolded into the measurement device.

Mean remolded shear strength of the grout is:	1.16 kPa
Remolded shear strengths for sediments from the Western North Atlantic, upper continental rise :	1.75 kPa

It should be noted that shear strength determined using a miniature vane shear apparatus is an undrained test to provide a value of cohesion for a natural sediment. Since the grout material is not truly cohesive but non-cohesive (granular) in behavior, the test performed on the grout material provides only qualitative results.

<u>(II) Subsequent Measurements at the NRL-SSC Laboratory</u>

(5) Calibration of the Volumetric Tubes

The volumetric tubes are 3 in. sections of nominally 2 in. diameter chromium stainless steel tubing. They are machined to fairly close tolerances, but the precision of data obtained from them is assured by individually marking, weighing, and measuring the volume of each in a climate controlled laboratory. Tubes weigh about 171 grams, and their volume is about 200 cc. The average precision of the tube volumes used is ± 0.01 cc with maximum values of ± 0.04 cc (Bennett et al., 1995).

(6) Pore Water Density

Solutes in the interstitial water, usually salts, alter the water density from that of pure water. Generally, the salts remain behind as the water evaporates. Therefore, for accurate values of derivative physical properties, those properties must be corrected for salinity in natural marine sediments. Salinity is determined from electrical conductivity or, in the present case, optical refractometry.

Index of refraction of water in the grout indicated that the salinity is extremely low and therefore can be neglected.

Salinity in marine sediments varies from surprisingly low to evaporite-like levels, but generally runs ~35 $^{o}/oo$ (parts per thousand) for sediments underlying open-ocean waters; and typical salinities for sediments from Chesapeake Bay range from 15-20 $^{o}/oo$ (Bennett et al., 1995).

(7) Grain Density Analyses

Average grain densities were measured on numerous samples of the grout using a Quantachrome Ultra-pycnometer (Quantachrome Corp., Boyton Beach, FL). This pycnometer determines the sample volume (sample weight is precisely known), and the grain density is calculated from the sample weight divided by the sample volume.

Precise grain density is a crucial parameter for the calculation of volumetric sediment properties, including percent gas, percent saturation, porosity, and void ratio. Determination of grain density to the nearest 0.005 g/cc is usually a totally routine measurement. Therefore, it was cause for concern when grain density measurements showed highly variable results from sample to sample.

Grain densities for the grout ranged from 2.50 g/cc to 2.95 g/cc, with single sample deviations ranging from 0.015 % to 0.60 %.

Grain densities for components of natural shallow-water marine sediments range from about 2.5 g/cc for certain diatom-derived opalized silica silts, to perhaps 2.85 for pyritic or dolomitic grains, and even higher for certain extremely rare minerals such as olivine. However, the quartz, feldspars, clay minerals, and other common constituents of normal littoral marine sediments have grain densities of 2.65 g/cc. Consequently, the grain density value of 2.65 g/cc (± 0.002 g/cc) shows up with monotonous regularity. Values for clay minerals in marine deposits, however, are somewhat higher (Bennett et al., 1980).

The surprising variability in the grain densities prompted a careful check of equipment and procedures. When no problem could be found, the grout was examined under the microscope, and the glass beads containing bubbles came to light. Several alternate procedures for preparing the grout samples for volume measurements were explored, but none gave confidence-inspiring results. This is examined further in the Discussion section.

(8) Scanning and Optical Microscopy Analyses

To ascertain the nature of the constituents of the matrix material, NRL examined the grout with both scanning electron and optical microscopes. The grout is composed of fly ash (glass needles and spheres); Aquigel (bentonite; a 2:1 hydrous aluminum silicate which is strongly hydrophilic and expandable); and Portland Cement (used for strengthening the material).

Grout mixtures recovered from 10 ft and 15 ft from GZ appeared identical under the optical microscope at magnifications of 160x to 400x for both pre-TZ and post-TZ samples, and for unground, gently ground, and very well-ground samples. About 50% of the dried samples consisted of amorphous to poorly crystalline groundmass, no doubt representing the Aquigel, bentonite, and Portland Cement content of the grout. The remaining 50% of the dried grout consisted of poorly-sorted glass spheres in the medium to very fine silt-size category (0.03 to 0.003 mm diameter), although a few grains were 0.04 to 0.05 mm in diameter (coarse silt size) or 0.07 to 0.10 mm in diameter (very fine-grained sand). Figure 2 shows the typical appearance of the grout at relatively low magnification. Both glass spheres and amorphous to poorly crystalline groundmass are present.

Optical microscopy revealed that the glass spheres from the fly ash varied widely in size. It also revealed that a significant percentage of them contained gas inclusions or vesicles (Figure 3). These bubbles occupied anywhere from a small part of the glass sphere to most of its internal volume. This no doubt is a cause of some of the wide range of densities for the grout. Figure 4 shows a glass sphere in which gas bubble inclusions appear to be associated with a crack in the sphere, but in most cases such damage was not readily evident. In Figure 5, a cross-section of a glass sphere shows that the sphere was hollow, and that a break in the outer surface of the sphere allowed it to become filled with water. However, Figure 6 shows part of a broken glass sphere in which the broken edge of the sphere indicates that it was mostly solid glass. Finally, Figure 7 is a scanning electron microscope photomicrograph of a broken glass

hemisphere. Different degrees of crushing to prepare the sample for average grain density determinations gave widely different values for grain density.

(9) Grain Size Distribution

Grain size analysis run on seven grout samples using standard textural analysis procedures resulted in mean values of sand, silt, and clay of 14.6%, 62.4%, and 22.0% respectively, classifying the grout as a sandy clayey silt.

(10) Remold Shear Strength vs. Time

A laboratory test was conducted on a substantial sample of the grout material in order to determine the "set up" potential of the grout vs. time. The test consisted of throughly mixing and remolding a large sample of grout, placing the material in a container suitable for making several undrained shear strength measurements, and determining the shear strengths at incremental time intervals. Water contents were determined and shear strength values calculated for the different timed tests (the test ran for a total of 1270 min from the time of remolding the sample). The data were fitted to an exponential "best fit" equation which gave a correlation of 0.88 (Figure 8). Separate tests run in the grout at 100 min time can be seen in Figure 8. The values for shear strength for the two tests are 0.61 kPa and 0.47 kPa, and the corresponding water contents are 85.8 % and 89.2 %, respectively. The relationship of water content to that of shear strength is shown in Figure 9. This inverse relationship (water content vs. undrained shear strength, Figure 9) is thought to be the cause of the variability for these two samples tested at 100 min. Although there may have been minor inhomogeneties within the remolded grout, the water content is thought to be the major factor in shear strength variability in addition to the set-up time period of the test.

(III) Derived Physical Properties

(11) Wet Bulk Density (γ_t)

Wet bulk density (γ_t) is the mass of the wet sediment sample in the volumetric tube divided by the volume of the tube (V_t).

Mean values for wet bulk densities of various marine sediments are:

Mean wet bulk density of the grout was	1.44 g/cc
Chesapeake Bay, clayey silt	1.36 g/cc
Western North Atlantic continental slope sediments	1.52 g/cc

The wet bulk density is not likely to be significantly affected by laboratory measurement procedures. However, if the shock wave crushes grains (hollow spheres) during the test, then post-TZ wet bulk densities could be slightly different from pre-TZ values.

Volume of the Solids (*Vs*)

Determination of this critical intermediate parameter depends upon highly precise measurement of the grain density (also, of pore water salinity; however, salinity in the grout is so low it can be neglected). Vs. is obtained by dividing the mass of the dried solids by their grain density (gm/gm/cc = cc).

Volume of the Voids (*Vv*)

Again, depending on the accuracy of grain density measurement, this quantity (*Vv*) is simply the volume of the tube minus the volume of the solid grains of the sample of material it contained.

(12) Void Ratio (*e*)

Void Ratio (*e*) is the volume of the voids divided by the volume of the solids.

Void ratio for the grout (average)	2.61
Chesapeake Bay samples (average)	3.52

(13) Porosity (η)

Porosity (η) is the percent voids per unit volume (*Vt*), or the volume of voids divided by the tube volume multipied by 100 %.

Mean porosity of the grout was	72.3%
Chesapeake Bay, clayey silt	75.3 %
Western North Atlantic continental slope sediments	71.0 %

(14) Percent (Water) Saturation of Pore Spaces (*S*)

Percent water saturation (*S*) is the weight of the water (plus any salt) divided by void volume, multiplied by 100 %.

Mean saturation value of the grout was	98.4 %
Chesapeake Bay samples (average)	97.0 %

Percent saturation (*S*) relates the degree to which the voids are occupied by the water. 100% saturation means there is no gas or air in the material.

(15) Percent Gas

This parameter is what is left over when all the solids, salts, and water are accounted for per unit volume. (Basically, it is the volume of the voids not occupied by water per unit volume.) A small error in grain density leads to a substantial error in calculated percentage gas; normally not a problem since grain density can usually be measured with great precision for a given sample. It is related to percent saturation by:

$$\%\ gas = ((1-S) \times \eta) \times 100\%$$

Mean percent gas values of the grout was	1.16 %
Chesapeake Bay samples (average)	1.83 %

DATA SYNTHESIS AND ANALYSIS

Various mass physical and index properties of the sediment were determined and plots made of the distribution of these parameters in the core (Figures 8 through 21). Tables 1 through 11 provide a statistical summary of the ranges of these measured and calculated data among cores (Tables 4 through 10), from pre-TZ to post-TZ time sequences (Tables 2 and 3), and averages using all cores to determine the nature of the physical properties and their ranges (Table 1)

Plots of water content vs. depth within the core, Figure 11, indicate a general trend for the water content to decrease with depth within the core. The pre-TZ core at 10 ft range from GZ showed the greatest range in water content values from greater than 130% near the surface to slightly above 80% at deeper depths. Generally, water content values from all cores, pre and post, averaged 100.8% (Table 1), with mean values of 100.2% (Table 2) pre-TZ, and 101.3% (Table 3) post-TZ. It is worth noting that effects on the physical properties seemed to vary depending on the amount of water that remained over the top of the cores in their plastic liner prior to extrusion and analyses, especially in *upper portions of the cores.*

"Natural" undrained shear strength values generally increase with depth and are also inversely proportional to the water content for the corresponding sampling interval, which is common in marine sediments (see Figure 9). Additionally, natural shear strength increased overall post-TZ as seen in the miniature vane shear data possibly due to the increased "set up" time since emplacement of the grout and the effect of the explosion on the material. Mean values of undrained shear strength from all the cores was 6.8 kPa (Table 1) with mean values for all pre-TZ and post-TZ cores increasing from 5.2 kPa (Table 2) pre-TZ to 7.8 kPa post-TZ (Table 3). Sensitivity, a dimensionless number derived from the ratio of natural shear strength at failure to the shear strength determined after remolding the sample, was calculated and plotted (Figure 17). Sensitivity values were high in the pre-TZ cores (values of nearly 15) and increased to values greater than 30 in remolded samples from post-TZ cores (mean values of 13.5 pre-TZ and 29.4 post-TZ). These values are generally considerably higher than those found for marine sediments on the continental margins of the East Coast of the U.S. (Lambert et al., 1981).

Plots of percent vane rotation to undrained shear strength from a pre-TZ and post-TZ core sampled at 15-ft range from GZ (Figures 18 and 19), using percent vane rotation normalized to 100% at the peak shear strength values, show that the shear strength of the pre-TZ core material varies from sample to sample more than in the

post-TZ core, as indicated in the tighter pattern of the data in the post-TZ core samples. Additionally, the apparent initial slope of the line in these plots appears to be steeper in the post-TZ core material indicating a tendency for failure to occur at less percentages of vane rotation when compared to the pre-TZ core (mean core values of 5.2 kPa pre-TZ to 7.8 kPa post-TZ (Tables 2 and 3). An increase in undrained shear strength to higher values in the post-TZ core samples is also shown in the plots.

Textural analyses run on the top, the middle, and the bottom of a pre-TZ and a post-TZ core, both cores 10 ft. from GZ reveal fairly consistent particle size distributions (Figure 20), with average values for percent sand, silt, and clay (seven samples) of :

		Average %	Standard Deviation
Sand	(2000-62.5μ)	14.6%	1.7
Silt	(62.5 to 3.9 μ)	62.4%	2.7
Clay	(< 3.9 μ)	23.0%	2.7

A tendency in the silts and clays for the particles to flocculate during pipette analysis required the addition of a deflocculating agent (sodium hexametaphosphate) to keep the particles in suspension. Figure 21, a ternary diagram of the percentages of sand, silt, and clay, shows a tight data point pattern that catagorizes all of the seven samples analyzed as clayey silts. The sample analyzed from a post-TZ core at 10 ft range, 123-125 cm depth, appears to be somewhat coarser than the other samples, as seen in the particle size distribution plot (Figure 20); however, this sample may have tended to flocculate during pipette analysis. Sand-sized particle distribution (2000-62.5 μ) was determined from one sample and is also shown in Figure 20.

Wet bulk density determinations of samples from the cores were measured with the precision volumetric tubes and values plotted. Derivative properties, i.e., porosity, void ratio, percent saturation, and percent gas were calculated using grain density values determined by the WES (2.63g/cc). NRL additionally analyzed select samples for average grain density, calculated the derivative properties, and compared the results with those obtained assuming a grain density value of 2.63 g/cc (value given by WES, phone conversation between B. Phillips and NRL). Figures 12 through 16 delineate these physical properties as related to depth within the core for both pre-TZ and post-TZ samples. Wet bulk densities tended to increase very slightly (0.01g/cc) from mean pre-TZ to mean post-TZ core values with a corresponding decrease in percent gas and an increase in percent saturation. Mean values for the parameters are 1.68% gas in the pre-TZ cores (Table 7) to 0.91% in the post-TZ cores (Table 3);

additionally, percent saturation increased from mean values of 97.7% before to 98.7% post-TZ (Tables 2 and 3). Mean porosity and void ratio values from pre-TZ and post-TZ cores are very similar, with mean porosity values of 72.4% and 72.2% pre-TZ and post-TZ respectively, and mean core void ratio values of 2.62 and 2.61 noted before and after TZ. Also, mean values of wet bulk density for all pre-TZ and all post-TZ cores were 1.43 g/cc pre-TZ to 1.44 g/cc post-TZ respectively (Tables 2 and 3).

An attempt to determine Atterberg Limits and related indices was unsuccessfull due to the material not "flowing" as required for the liquid limit test and/or the inability of the material to be kneaded and rolled for the plastic limit. The large percentage of silt-sized particles (62.5-3.9 μ) and the mobility of the water in the grout are considered likely causes for not being able to determine Atterberg Limits. The material's surface chemistry did not allow for strong bonding of the water to the particle surfaces. Typical marine sediments contain clays which have a high surface area-to-mass ratio, and these surfaces are largely negatively charged. Water, a polar, charged molecule, will molecularly align and attach to these charged clay surfaces, thus readily bonding the water to the clay mineral.

DISCUSSION

Appendix C, a table of mean index property values from Patuxent River/Chesapeake Bay, MD samples, and Appendix D, a comparison of geotechnical data from four sedimentary provinces of the western North Atlantic (extracted from Bennett et al., 1980), are provided for a comparison of data values between the natural environment and those values determined from the "synthetic sediment."

Appendix D relates geotechnical property data from cores taken in oceanic waters which are considerably deeper than the littoral zone and of sediments containing much greater but common percentages of clay particles.

Comparing the mean geotechnical property values of the clayey-silt samples from Chesapeake Bay/Patuxent River (Appendix C) to mean values of those properties determined in the BEAST Calibration Test grout (Table 1) reveals that mean values from all the BEAST cores have slightly higher grain density values (2.63 g/cc *vs* 2.59 g/cc), slightly lower porosities (72.3% *vs* 75.3%), higher undrained shear strength values (6.8 kPa *vs* 3.8 kPa), and lower water content values (100.8 % *vs* 126.3%). Additionally, percent gas (air) values from the BEAST Test are less (1.16 % *vs* 1.83%), percent saturation values were higher in grout samples (98.4 % *vs* 97.0 %), as were void ratio values (2.61 in the grout *vs* 2.46 in the bay/river samples). The following shows the reported comparison of the important index properties:

Mean Index Values	Clayey Silt Samples from Patuxent River/Chesapeake Bay	BEAST Calibration Test
water content	126.3 %	100.8 %
percent gas	1.83 %	1.16 %
percent saturation	97.0 %	98.4 %
wet bulk density	1.36 g/cc	1.44 g/cc
average grain density	2.59 g/cc	2.63 g/cc
porosity	75.3 %	72.3 %
void ratio	2.46	2.61
shear strength	3.8 kPa	6.8 kPa
% sand, silt, and clay	12.7%, 58.1%, 29.1%	14.6%, 62.4%, 23.0%

NRL determined average grain densities on samples and subsamples of the grout using a Quantachrome Ultra-pycnometer (Quantachrome Corp., Boyton Beach, FL). The pycnometer determines the sample volume (sample weight is precisely known) and the average grain density is calculated from the sample mass divided by the sample volume. The precision for the pycnometer for grain density is reported to be on the order of 10^{-4} g/cc. Generally, a sample's volume is determined by multiple sample runs until a deviation between the measured volumes is no greater than approxmately 0.005%. Standard operating procedure requires that the machine be recalibrated weekly to a standard of known volume. NRL routinely runs daily volume calibrations to determine the density of standards (calibration sphere density = 1.0000 g/cc and Ottawa sand (pure quartz), density = 2.65 g/cc). During the analysis of the grout samples, daily density calibration results for the calibration sphere were ±0.0005 g/cc, and for the quartz standard were ±0.008.

Initially, average grain density determinations were run on samples which were either gently disaggregated mechanically or ground in a mortar and pestle to evaluate the variability of grain density of the grout. The effect of the variability of average grain density on the derivative properties (percent gas, percent saturation, void ratio, and porosity) are presented in graphs and tables in Appendix E.

The results of average grain density runs for the grout were highly variable both for repeated runs on single samples and among several samples. Grain densities for the grout ranged from 2.50 g/cc to 2.95 g/cc, with single sample deviations ranging from 0.015 % to 0.60 %. The low grain density values were derived from gentle

mechanical disaggregation of samples and the higher values were derived using standard disaggregation techniques (mortar and pestle) (see Table 11). The plausible explanation for the higher densities seems to be that the increases in values are due to the fracturing of hollow spheres, with an effective decrease in volume of solids, which drives the numerical value of grain density up. It should be noted again that the grain density values varied greatly throughout the numerous samples tested.

Since the June meeting at NSWC-WO, NRL's Geotechnical Team has conducted additional materials tests and evaluations of the grout material used for the initial shock wave tests conducted at WES. NRL (Bennett) has been in contact with WES (Phillips) regarding the grout material characteristics and properties, and tests continued at WES to determine additional properties of the material, such as crushing strength of the spheres and additional grain density measurements.

During a phone conversation with Bennett, Phillips reported grain densities of 2.53, 2.59, and 2.70. He also indicated that the heavily ground material (rock grinder) gave densities of 2.70 and the mortar and pestle ground material gave densities of 2.53 and 2.59. These data are consistent with the NRL tests conducted on the material and data Bennett presented at the June 1995 meeting at NSWC-WO.

Additional tests and observations have revealed further evidence that the grinding and dispersing of the grout breaks some of the spheres (usually the largest ones appeared to be most affected by grinding) which have gas entrained in the cavities and that when this occurs the measurement of grain density is significantly changed. Generally, the heavier the grinding, the higher the grain density; since the grain density is a mass per unit volume measurement, when a "hollow" sphere is broken, the effective volume is decreased and the grain density measurement is driven to a higher value.

To understand the uncertainty in the volumetric measurements as a function of the variable grain densities, we selected what we consider a reasonable range of grain density values and calculated percent gas, percent saturation, porosity, and void ratio. We used a low value of 2.53g/cc observed by both WES and NRL, a more frequently observed low value of 2.60g/cc, an "average" value of 2.72 g/cc, and a high value of 2.83g/cc (Table 11). Data from Core 10 were used to make the comparison of the effects. Plots of these data are presented in Figures 22-25. Note that grain density differences of only 0.2 to 0.3 g/cc result in a considerable range in calculated gas content and saturation. This indicates a disturbingly high degree of uncertainity in the material properties of the grout, *particularily the gas content* (in some cases two orders of magnitude difference).

CONCLUSIONS

Careful analysis of the geotechnical data sets from the BEAST Calibration Test have revealed significant similarities and differences noteworthy for consideration of future work with the grout for testbed purposes. The authors summarize the following findings: shear strength data (natural and remolded) appear to be reasonably good measurements. Physical property measurements including water content, wet bulk density, dry bulk density, and textural analysis (gross grain size) appear to be reasonable and of high quality.

Highly questionable data include grain density, which was observed to be highly variable and largely dependent upon the technique used to disaggregate the dry solids for measurement in the pycnometer. Gentle mechanical disaggregation provided the lowest grain density values on average and rigorous grinding in a mortar and pestle provided the highest grain density values. The differences and variability in the grain densities significantly effects volumetric measurements of gas content, percent saturation, porosity, and void ratio.

Shear strength values were generally highly variable and indicated a high degree of inhomogeneity with general trends observed, such as increases in shear strength with depth within core, and less variability of shear strength values in post-TZ core analysis. It should be noted, however, that a test run to determine possible effects of time on shear strength revealed significant increases in shear strength (2-2.5 times the values within approximately 20 hours, Figure 8).

In summary, the grout material appears to be highly variable in physical and mechanical properties and comparative analysis with natural marine sediments reveals significant differences. The greatest concern appears to be the inability to obtain reliable grain density measurements and, thus, confidence in the derivative physical property determinations (percent gas, percent saturation, porosity, and void ratio).

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REFERENCES

American Society for Testing Materials (1958). Book of ASTM Standards, Including Tentatives, Part 4, Philadelphia, PA.

Bader, R. G. (1957). A Study of Local Variability in Marine Sediments, *Proceedings of the 8th Pacific Science Congress of the Pacific Science Association, Nov. 1953, Vol. 3,* Oceanography, National Research Council, Quezon, Philippines, p. 721-732.

Bennett, R. H., Keller, G. H., and Busby, R. F. (1970). Mass Property Variability in Three Closely Spaced Deep-Sea Sediment Cores, *Journal of Sedimentary Petrology,* **40**, No. 3, Sept., pp 1038-1043.

Bennett, R. H., Lambert, D. N., and Hulbert, M. H. (1977). Geotechnical properties of a submarine slide area on the U.S. continental slope northeast of Wilmington Canyon. Marine Geotechnology, 2 (Marine Slope Stability), pp 245-261.

Bennett, R. H., Freeland, G. L., Lambert, D. N., Sawyer, W. B., and Keller, G. H., (1980). Geotechnical Properties of Surficial Sediments in a Mega-Corridor: U.S. Atlantic Continental Slope, Rise, and Deep-sea Basin, Marine Geology, 38, pp 123-140.

Bennett, R. H., Lavoie, D. M., Sawyer, W. B., Hunter, N. W., Meyer, M. M., Kennedy, C. S., McCrocklin, K. H., Lavoie, D. L. (1995). Geotechnical and Biogeochemical Properties of Sediments from Chesapeake Bay: Mass Physical and Mechanical Properties of Sediments Near the Mouth of the Patuxent River, p. 164.

Ford, M. B. (1995). Shallow Water Mine Warfare Experiments: Calibration Test Layout and Construction, presented at DNA Shallow Water Test Series Planning Meeting, Naval Surface Warfare Center, White Oak Detachment, Silver Spring, MD, 13 June 1995.

Ford, M. B. and Phillips, B. R. (1995),. Ouick Look Report for the BEAST Calibration Test, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS, p.53.

Goertner, J. A. (1995). BEAST Pre-Test Calibration Shot, Report on Test Operations, Indian Head Division / White Oak, Naval Surface Warfare Center, Silver Spring, MD, p. 30.

Goodwin, R. W., (1993). *Combustion Ash/Residue Management, an Engineering Perpective*, (Noyes Publications, Park Ridge, NJ), p. 85.

Kenney, T. C. and Landva, A. (1965). Vane-Triaxial Apparatus: *Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering,* Montreal, Canada, Vol. 1, p. 269-272.

Lambe, T. W. (1951). *Soil Testing for Engineers*, John Wiley & Sons, Inc., New York, NY.

Lambert, D. N., Bennett, R. H., Sawyer, W. B., and Keller, G. H., (1981). Geotechnical Properties of Continental Upper Rise Sediments-Veatch Canyon to Cape Hatteras, Marine Geotechnology, V4.,4, p. 281-306.

Phillips, B. R. (1995). Shallow Water Mine Warefare Experiments: Calibration Test Sediment Results, presented at DNA Shallow Water Test Series Planning Meeting, Naval Surface Warfare Center, White Oak Detachment, Silver Spring, MD, 13 June 1995.

Richards, A. F. (1964). Local Sediment Shear Strength and Water Content, In *Papers in Marine Geology, Shepard Commemorative Volume*, Miller, R. L. (ed.), The MacMilliam Company, New York, NY, p. 474-487.

Sandler, I. S. (1995). Computational Analysis of the BEAST Calibration Shot, Weidlinger Associates, New York, NY, p. 75.

Sowers, G. B. and Sowers, G. F. (1951, revised 1961). *Introductory Soil Mechanics and Foundations, Second Edition*, The MacMillan Company, New York, NY.

Terzaghi, K. and Peck, R. B. (1967). *Soil Mechanics in Engineering Practice*, John Wiley & Sons, Inc., New York, NY.

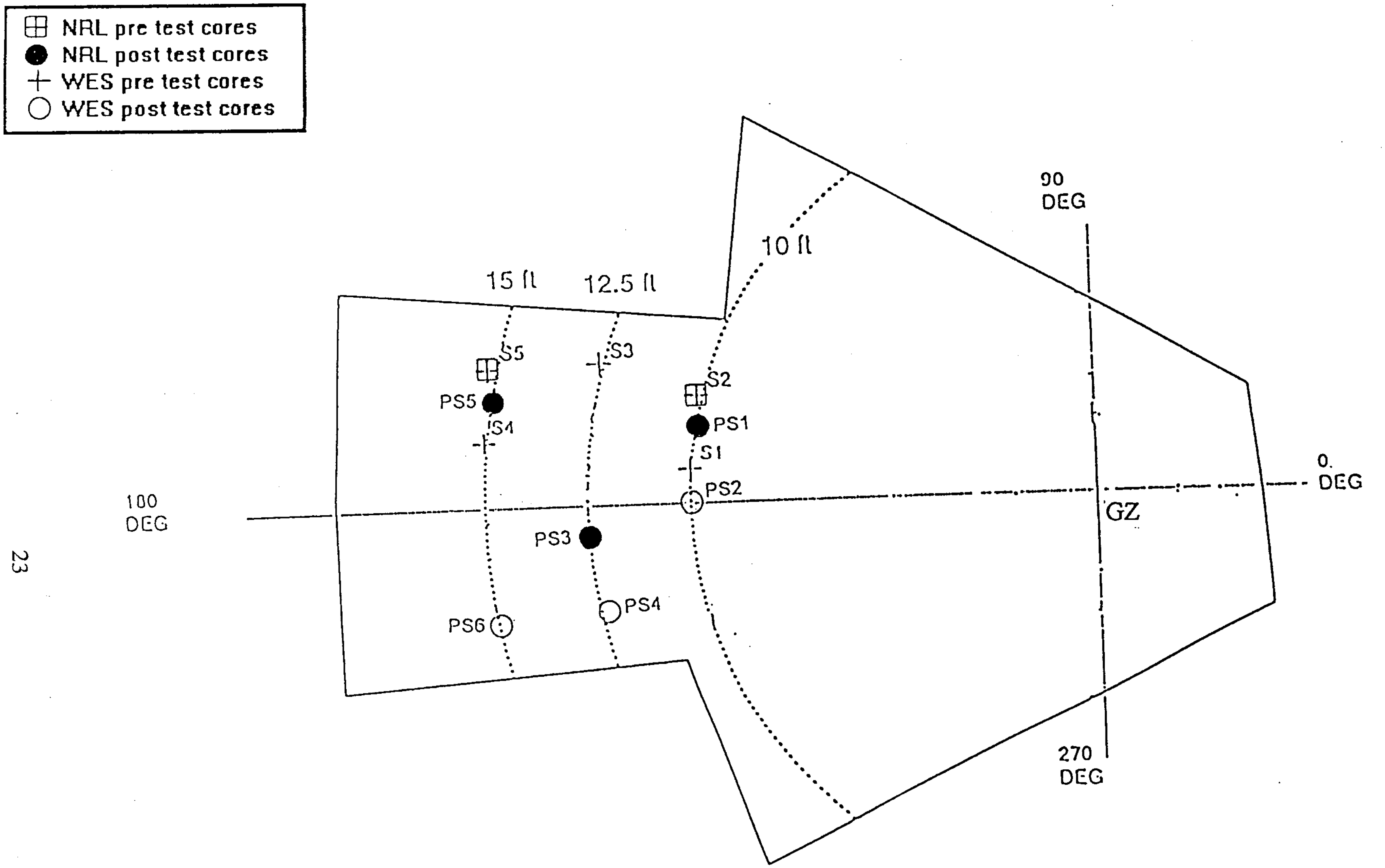


Figure 1. BEAST Calibration Test layout and sample locations (S indicates pre- GZ samples and PS indicates post- GZ samples).

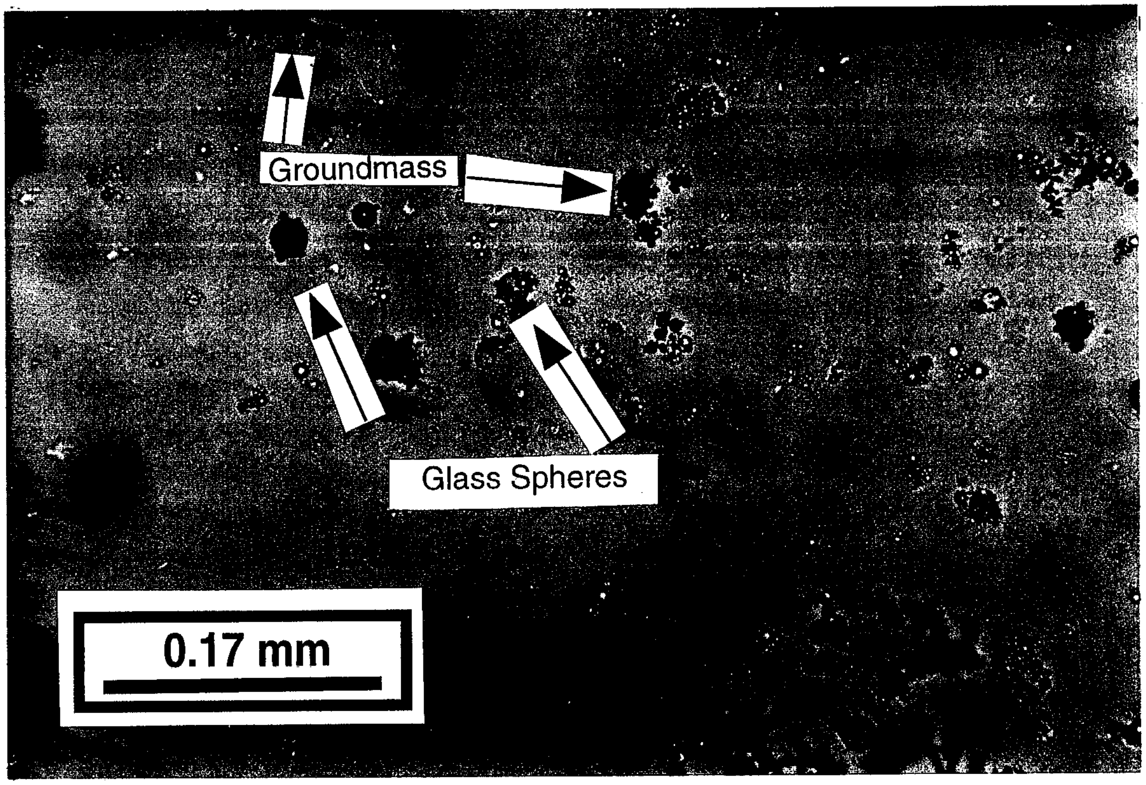


Figure 2. Big Black 15 Post(-Blast) 9. Unground grout sample. 160x original magnification, unpolarized transmitted light. Typical field of view of poorly crystalline to amorphous groundmass and glass spheres.

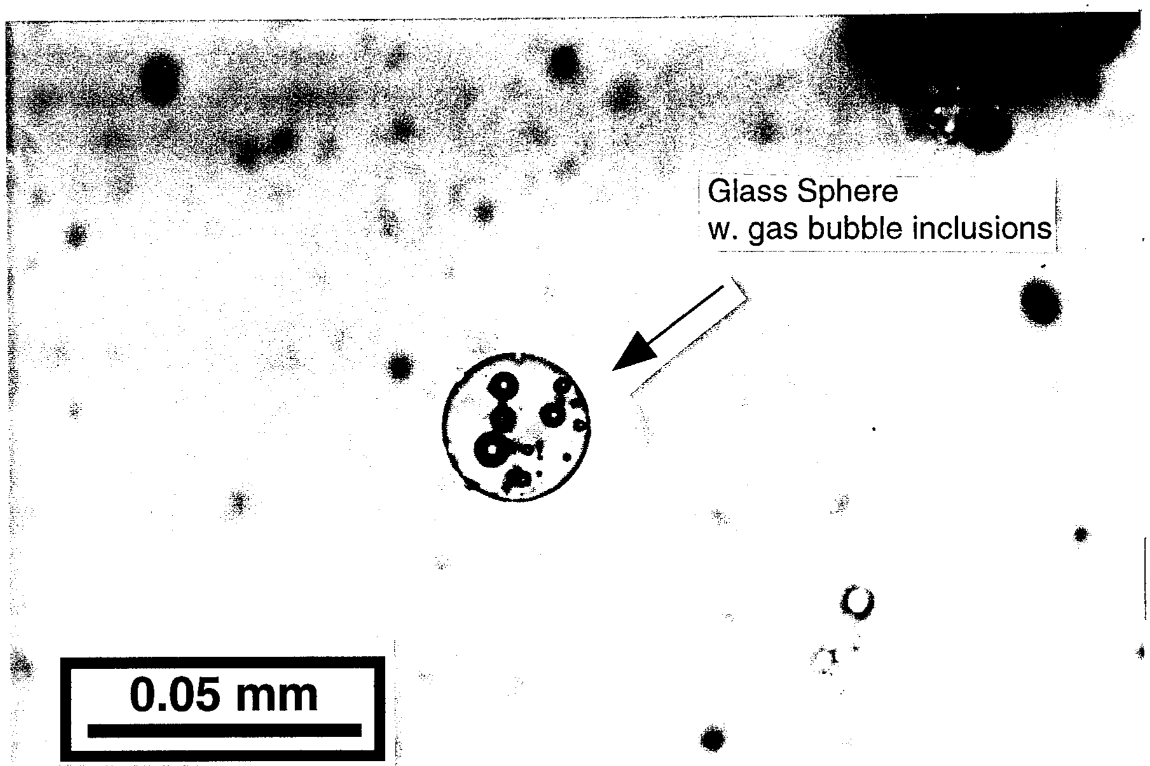


Figure 3. Big Black 15 Post(-Blast) 9. Gently ground in mortar and pestle. 400x original magnification, unpolarized transmitted light. 0.04 mm diameter glass sphere with numerous gas bubble inclusions.

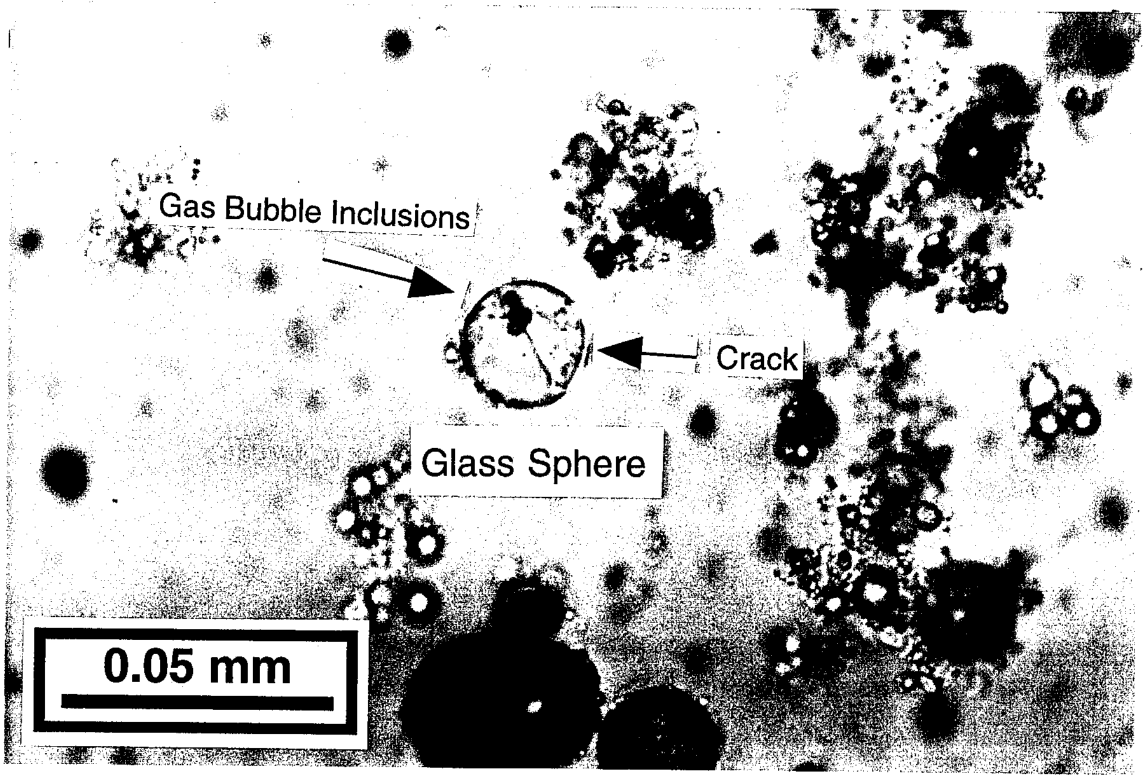


Figure 4. Big Black 15 Post(-Blast) 9. Gently ground in mortar and pestle. 400x original magnification, unpolarized transmitted light. 0.03 mm diameter glass sphere in center of field of view, with gas bubble inclusions associated with crack in sphere.

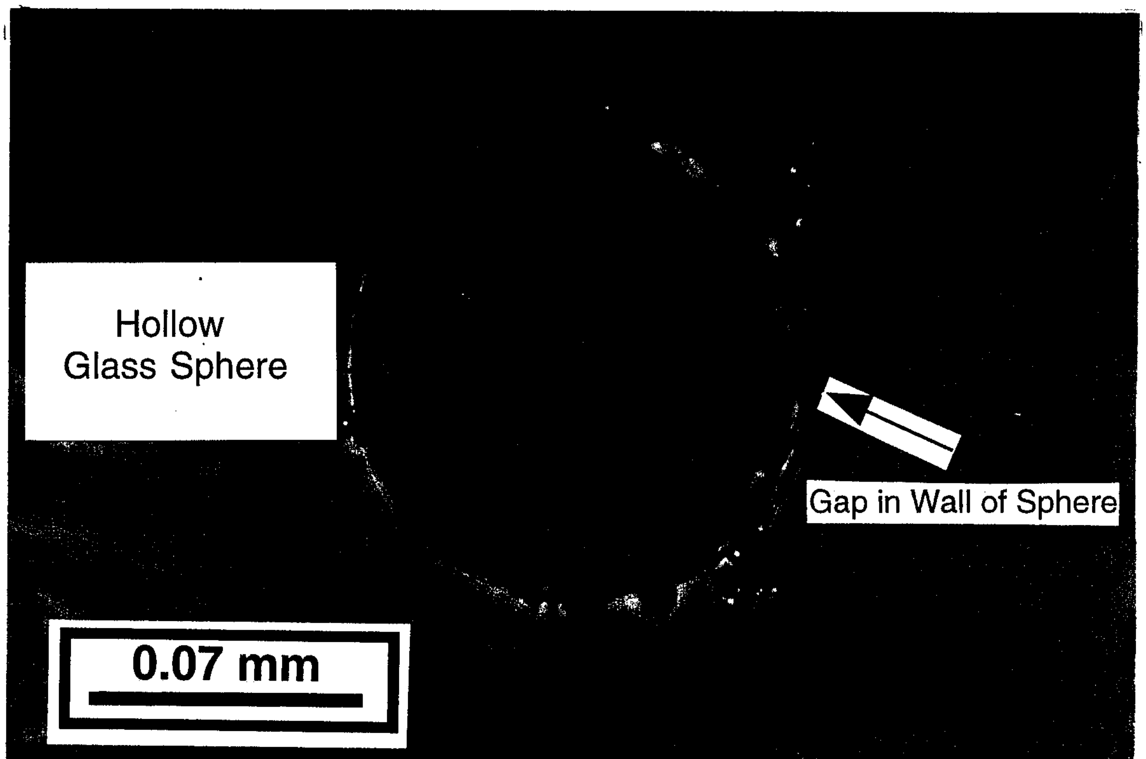


Figure 5. Big Black Post(-Blast) 9. Slightly ground in mortar and pestle. 400x original magnification, unpolarized transmitted light. 0.10 mm diameter hollow glass sphere.

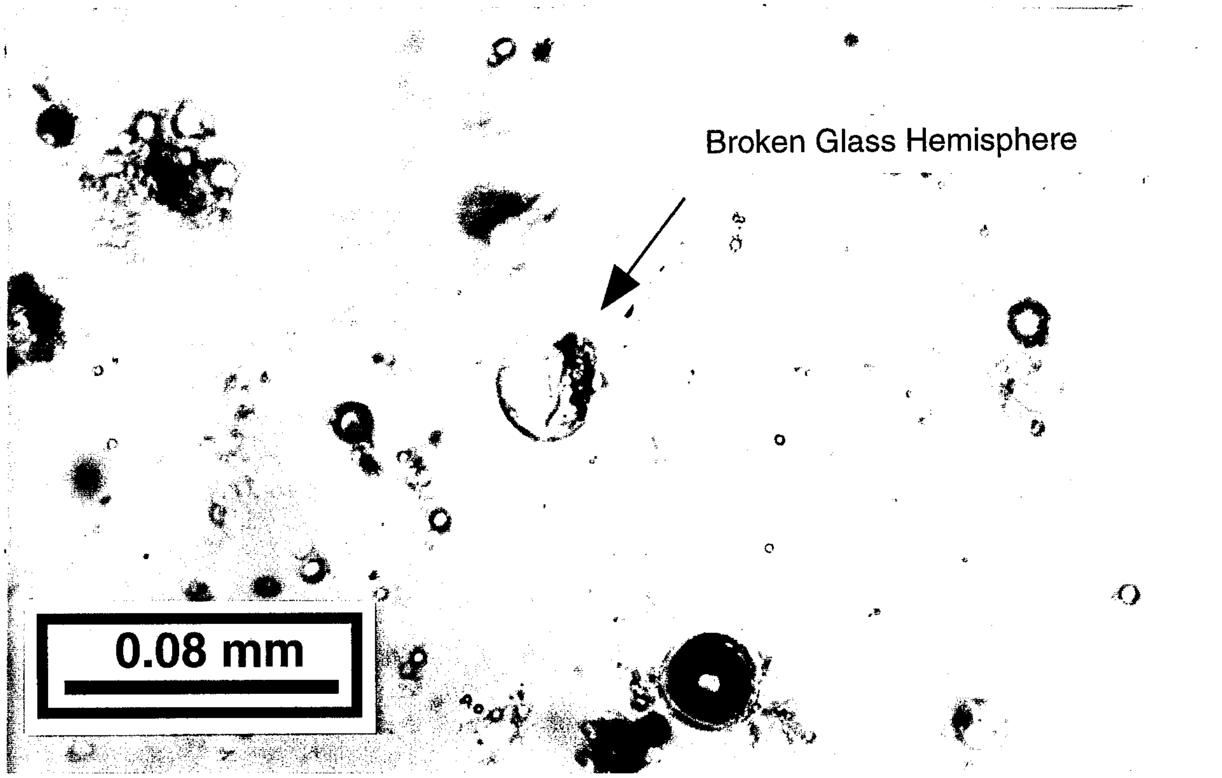


Figure 6. Big Black Post(-Blast) 9. Gently ground in mortar and pestle. 250x original magnification, unpolarized transmitted light. 0.04 mm diameter broken glass hemisphere in center of field of view.

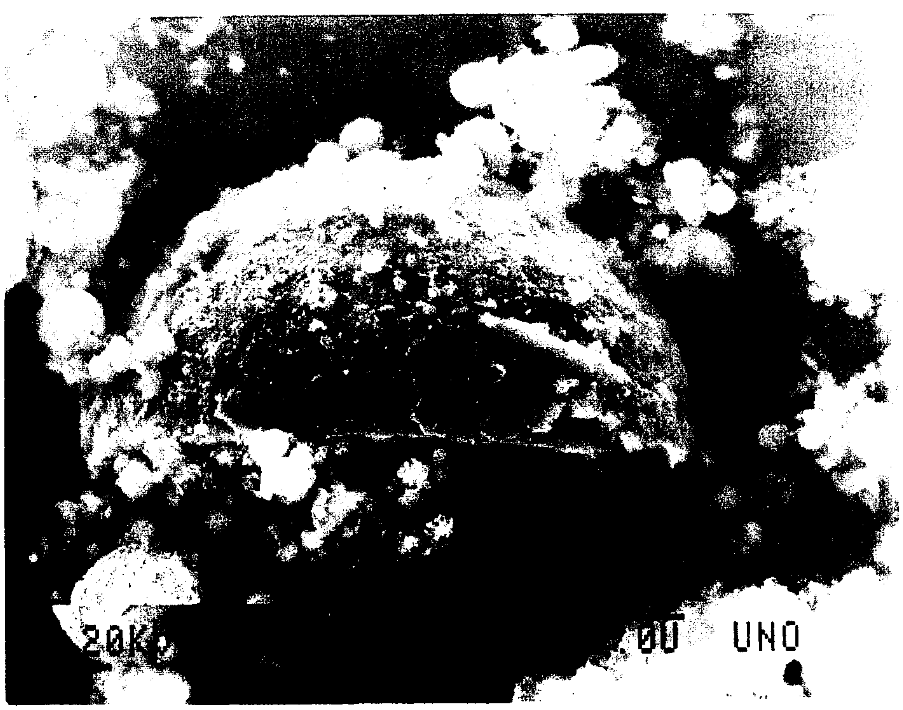


Figure 7. Big Black Post(-Blast)9. Very well-ground in mortar and pestle. SEM photomicrograph, 1800x original magnification. Broken glass hemisphere.

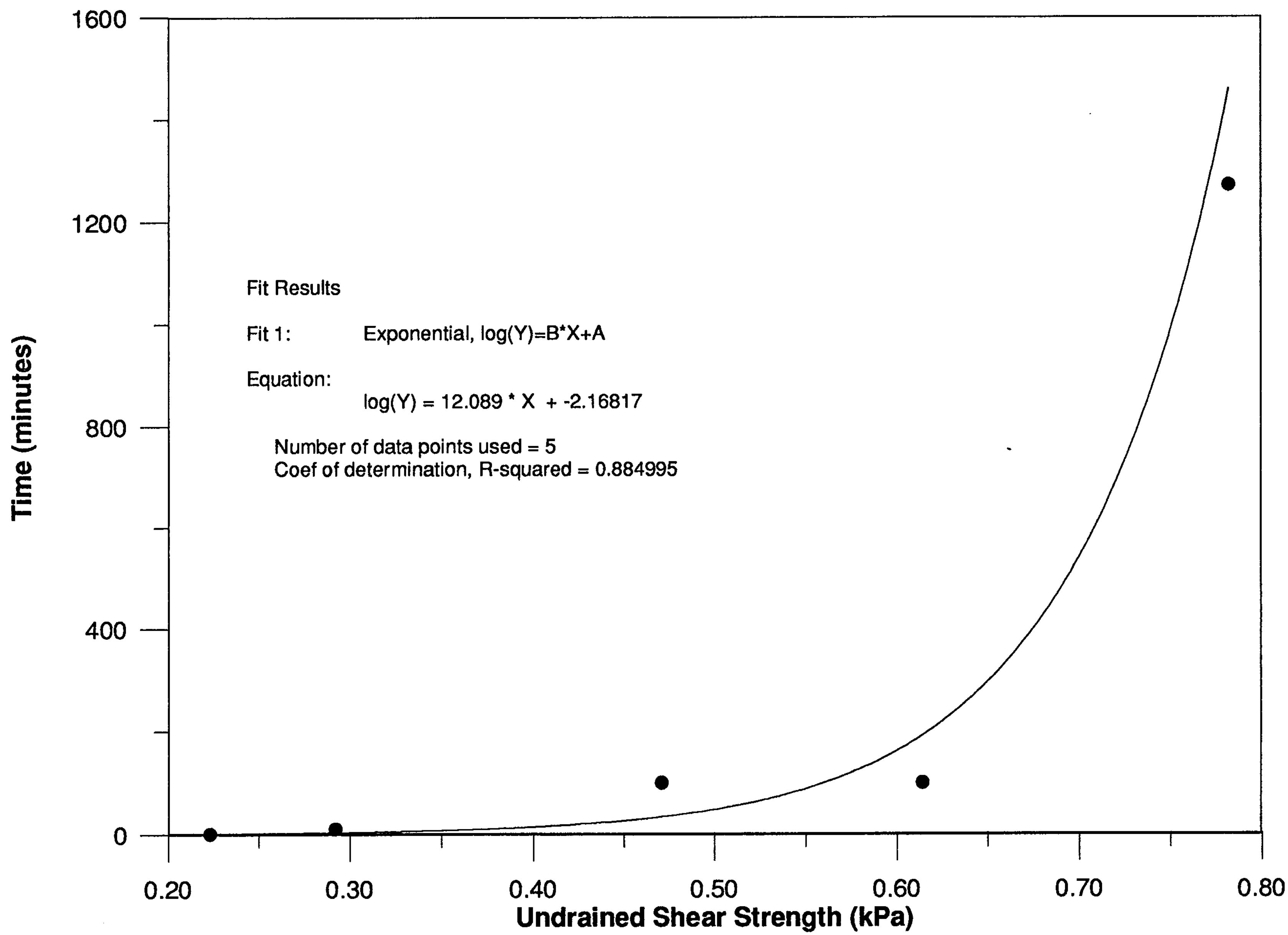


Figure 8. Undrained shear strength versus "set up" time of a remolded BEAST grout sample.

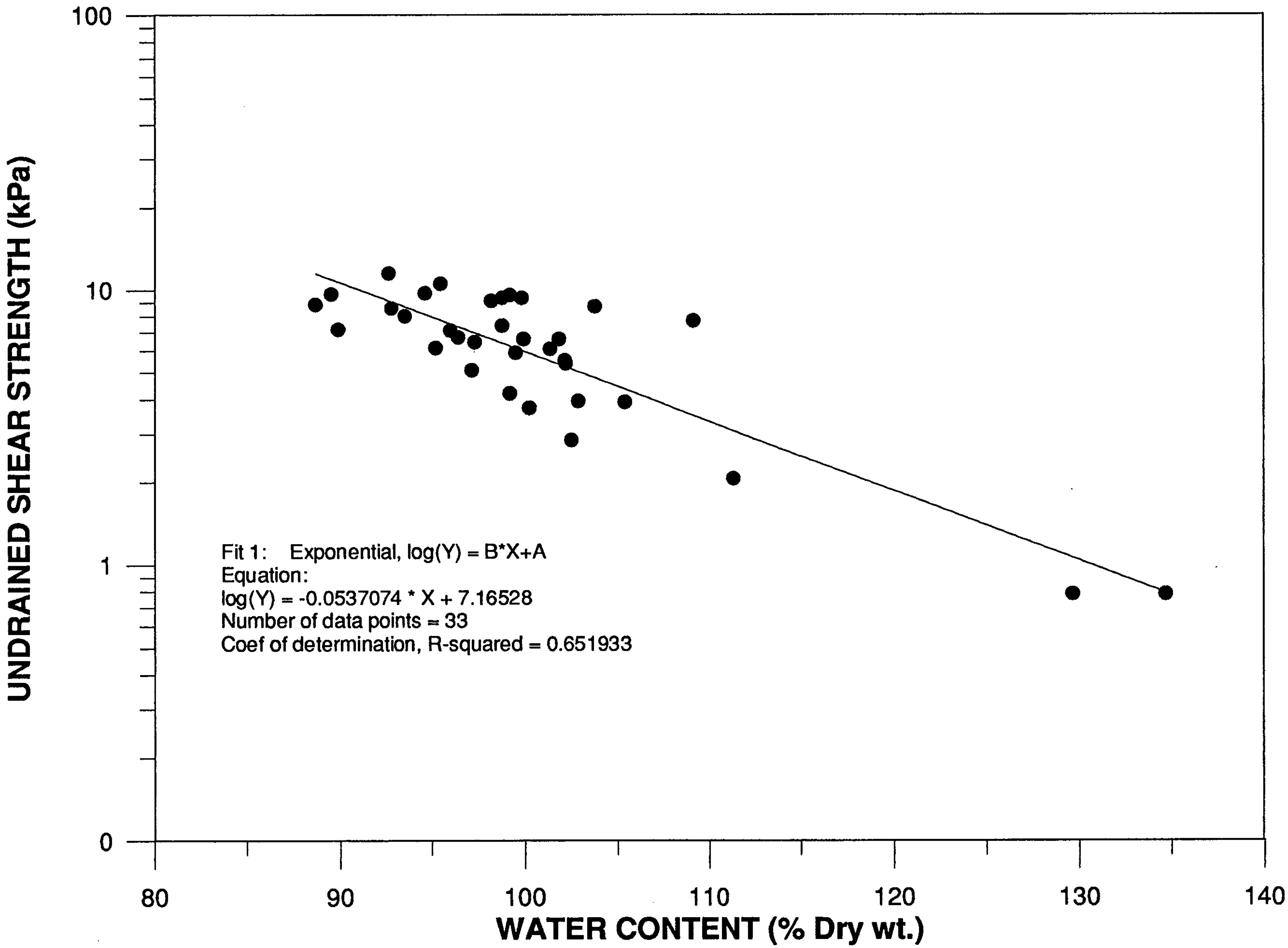


FIGURE 9. **Plot of water content versus undrained shear strength for all calibration test cores, pre and post time zero (TZ).**

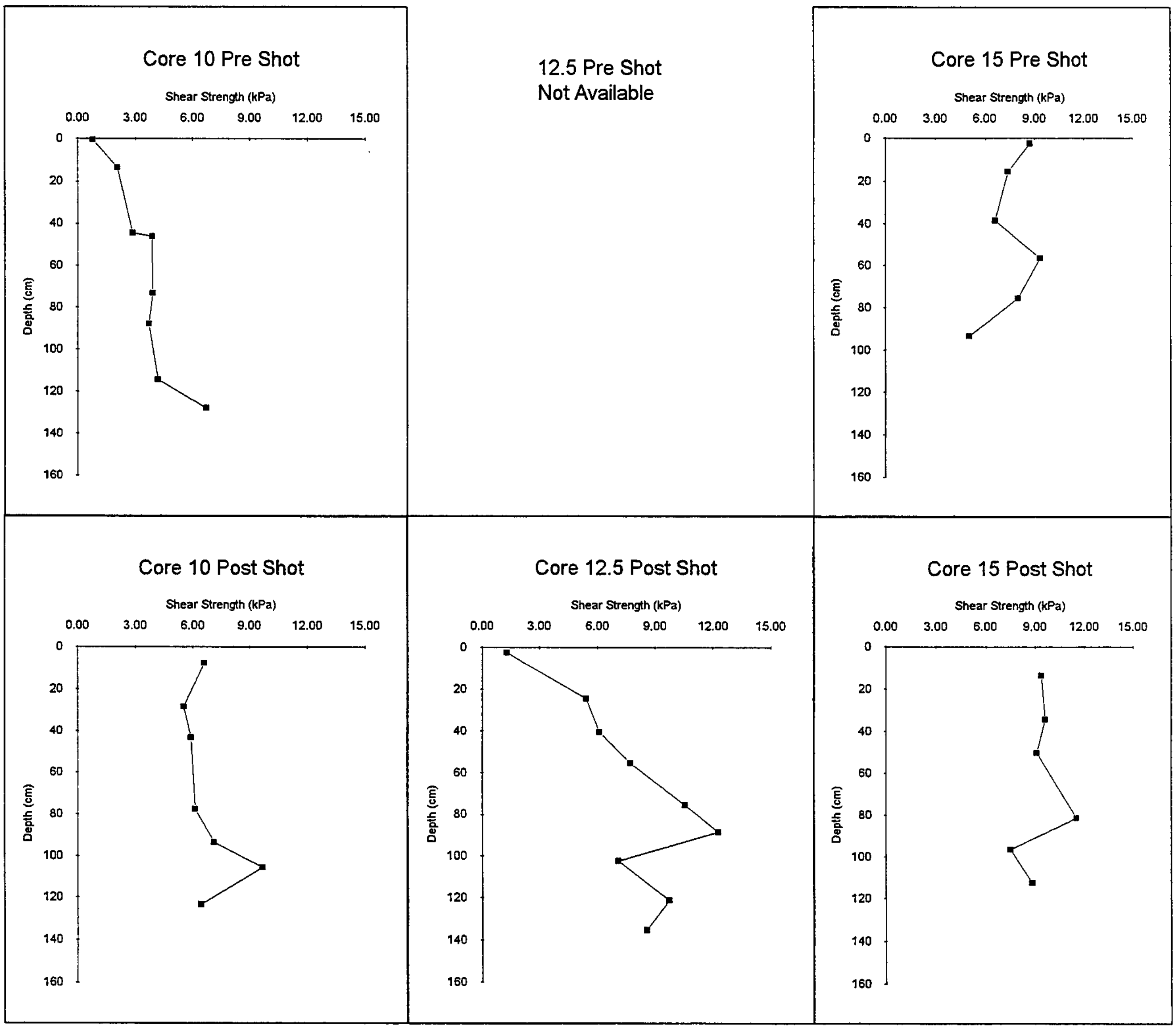


Figure 10: Plots of Undrained Shear Strength (kPa) for pre- and post- shot cores.

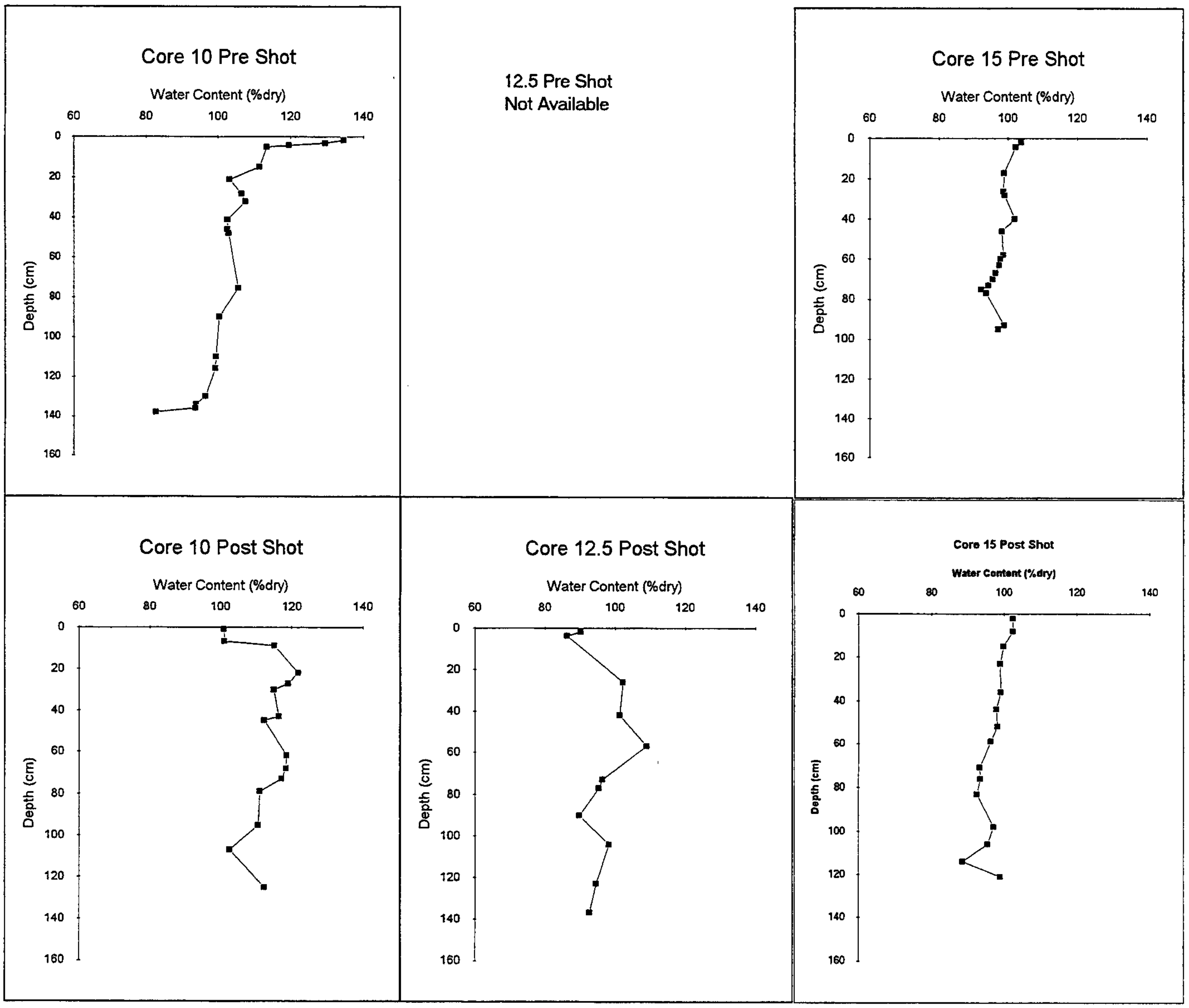


Figure 11: Plots of Water Content (%dry weight) for pre- and post- shot cores.

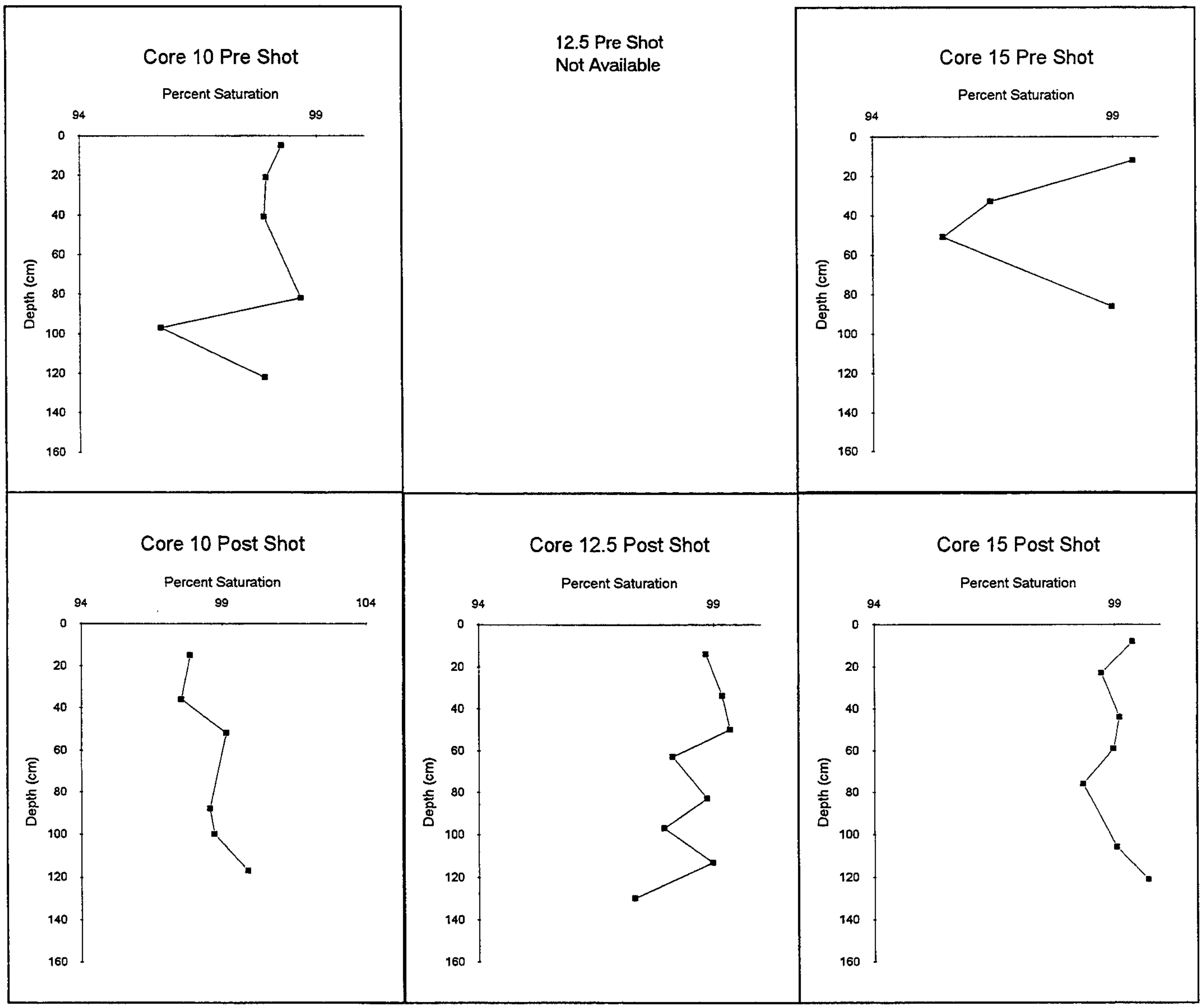


Figure 12: Plots of Percent Saturation (using an average grain density of 2.63 g/cc) for pre- and post- shot cores.

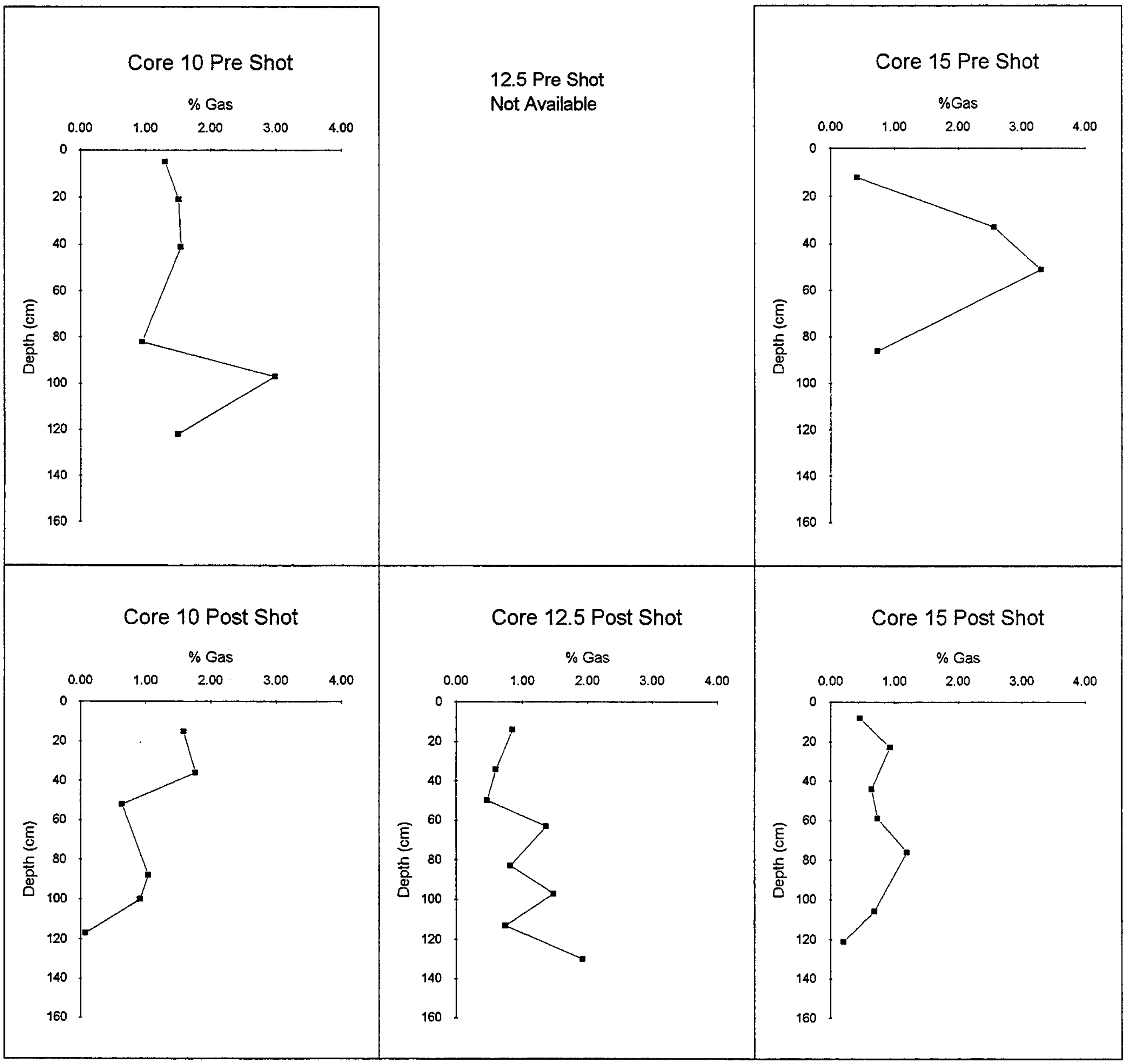


Figure 13: Plots of Percent Gas (using an average grain density of 2.63 g/cc) for pre- and post- shot cores.

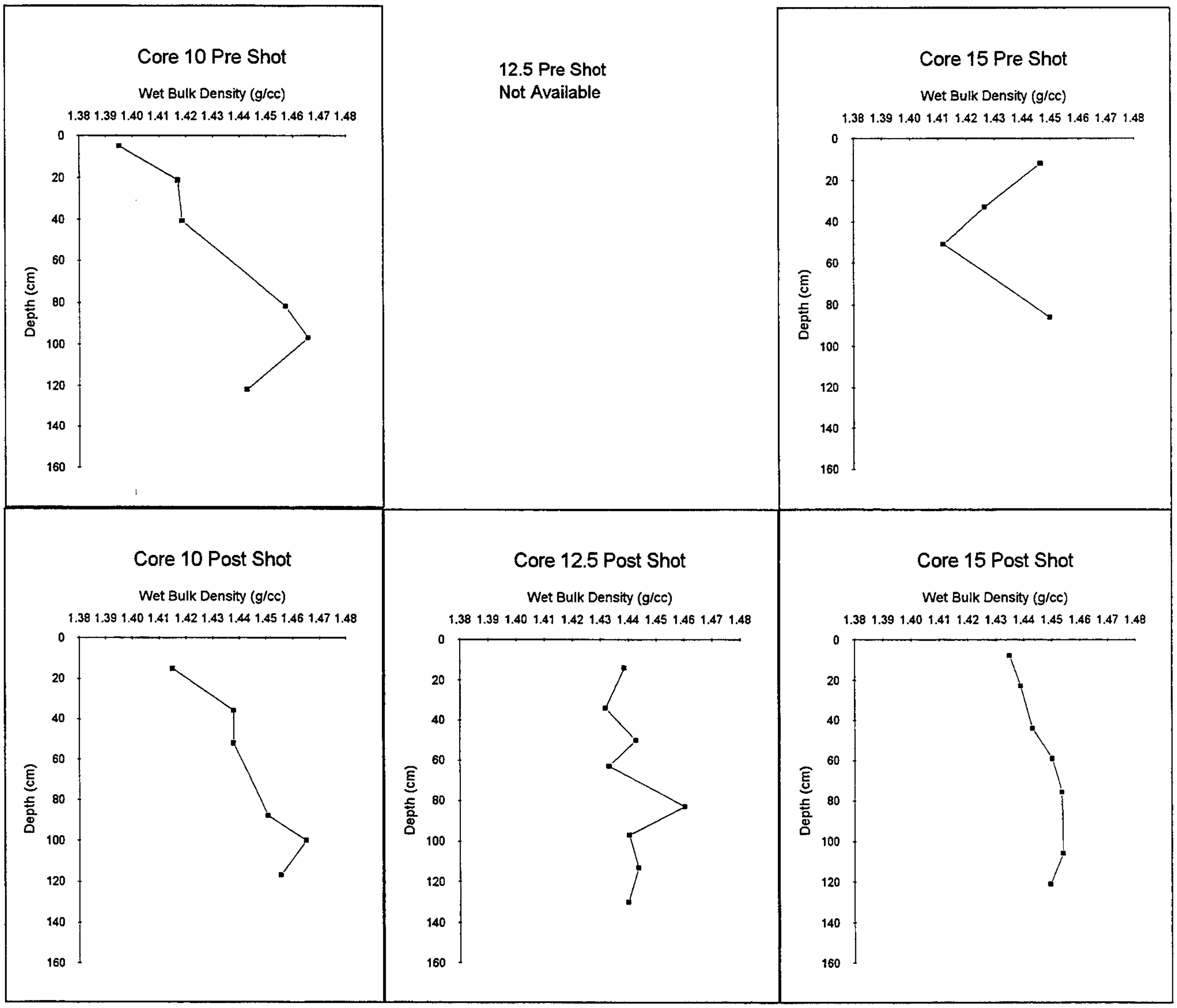


Figure 14: Plots of Wet Bulk Density (g/cc) for pre- and post- shot cores.

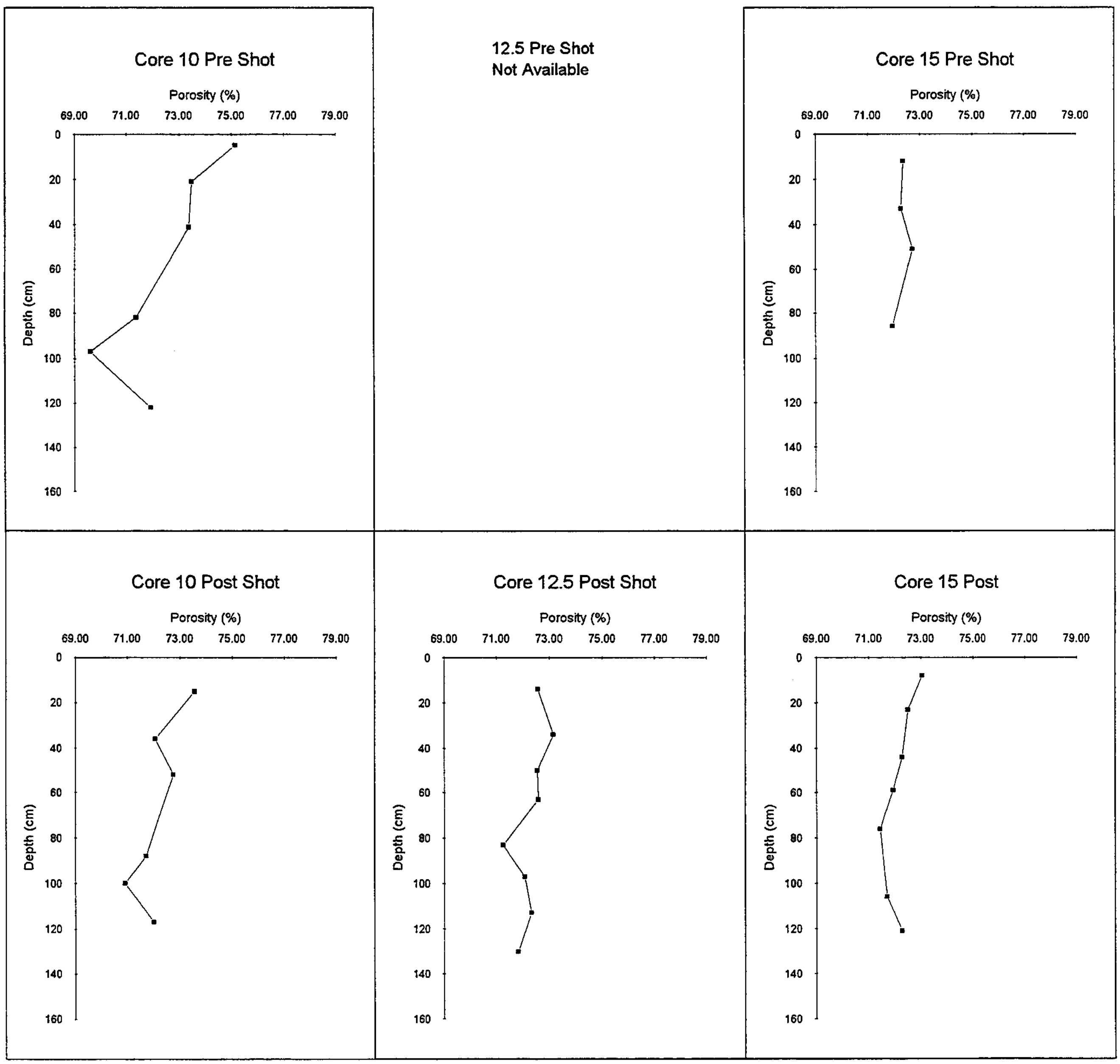


Figure15: Plots of Porosity (%)(using an average grain density of 2.63 g/cc) for pre- and post- shot cores.

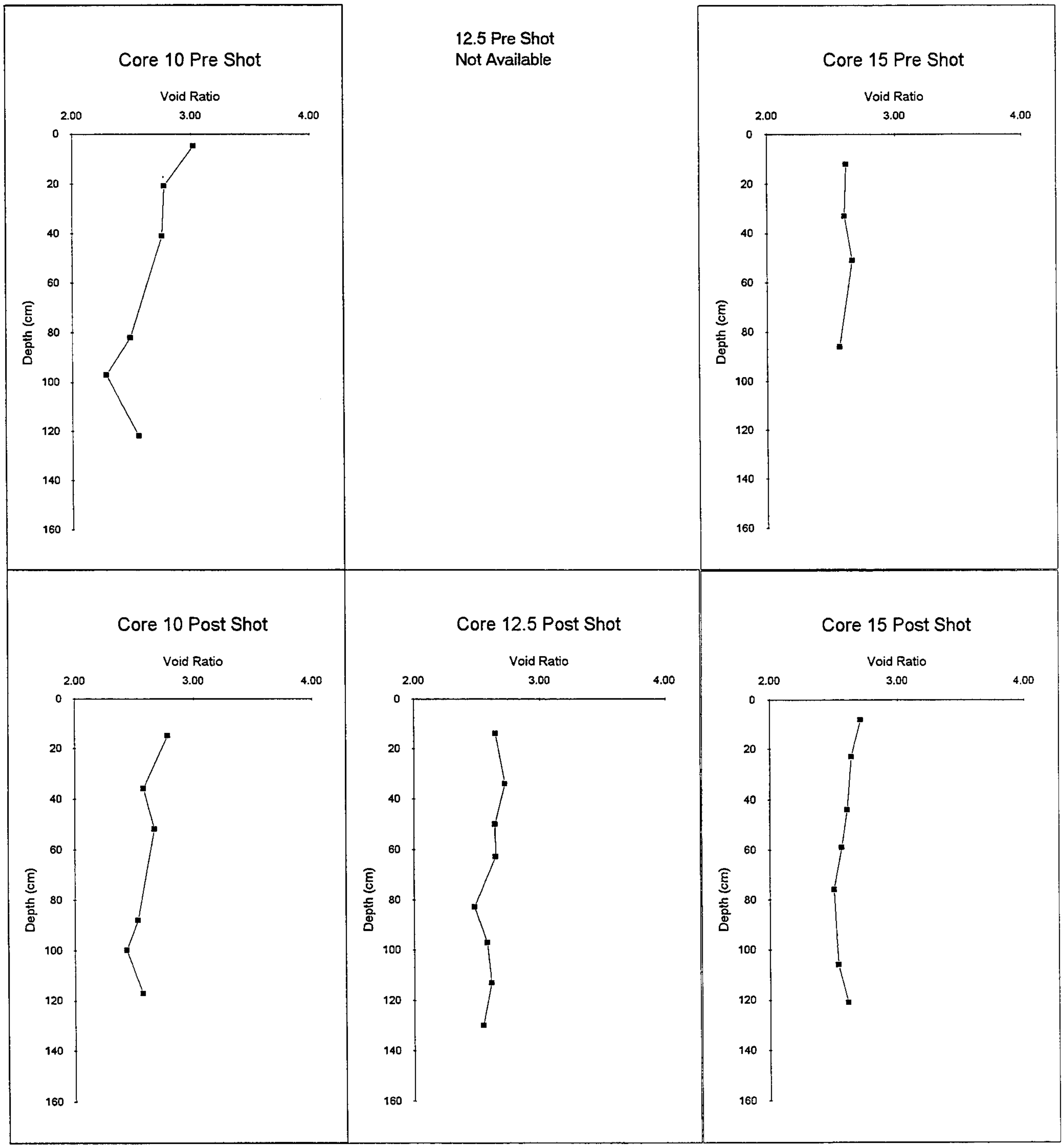


Figure 16: Void Ratio plots (using an average grain density of 2.63 g/cc) for pre- and post- shot cores.

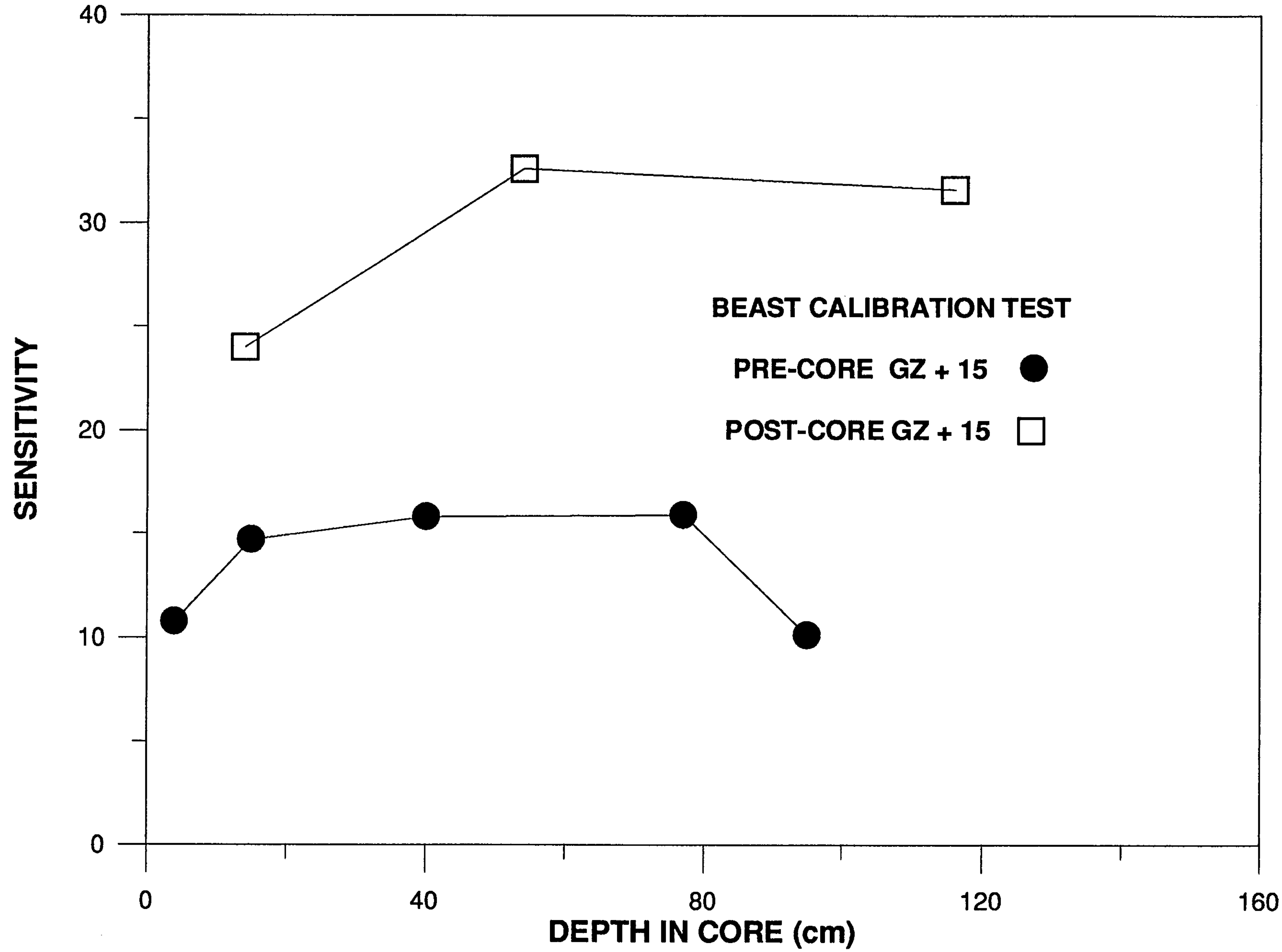


Figure 17. Plot of sensitvity, ratio of undrained natural shear strength to that of sample after remolding.

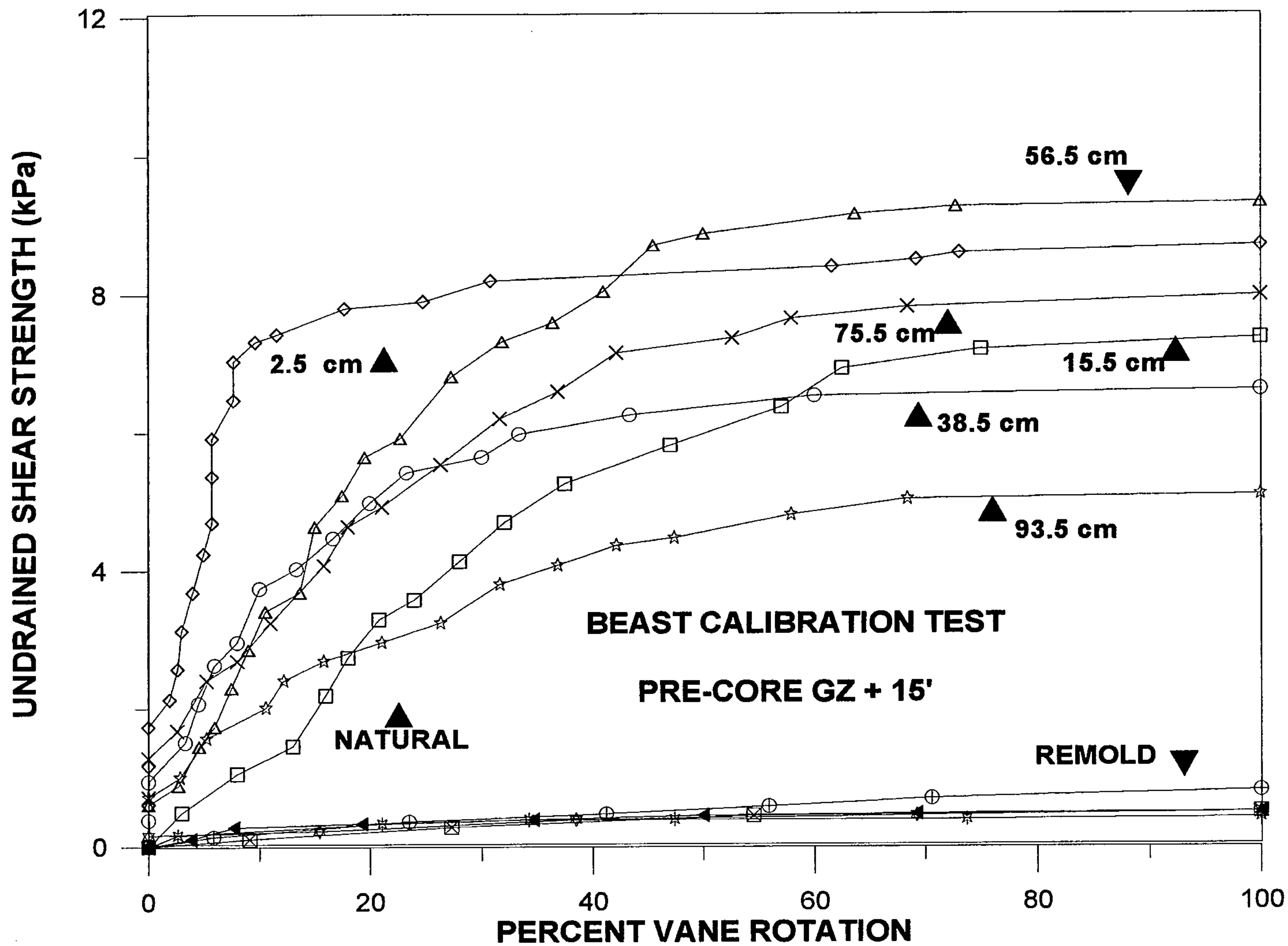


Figure 18. Plot of percent vane rotaion versus undrained shear strength for both the natural and remolded state of the material.

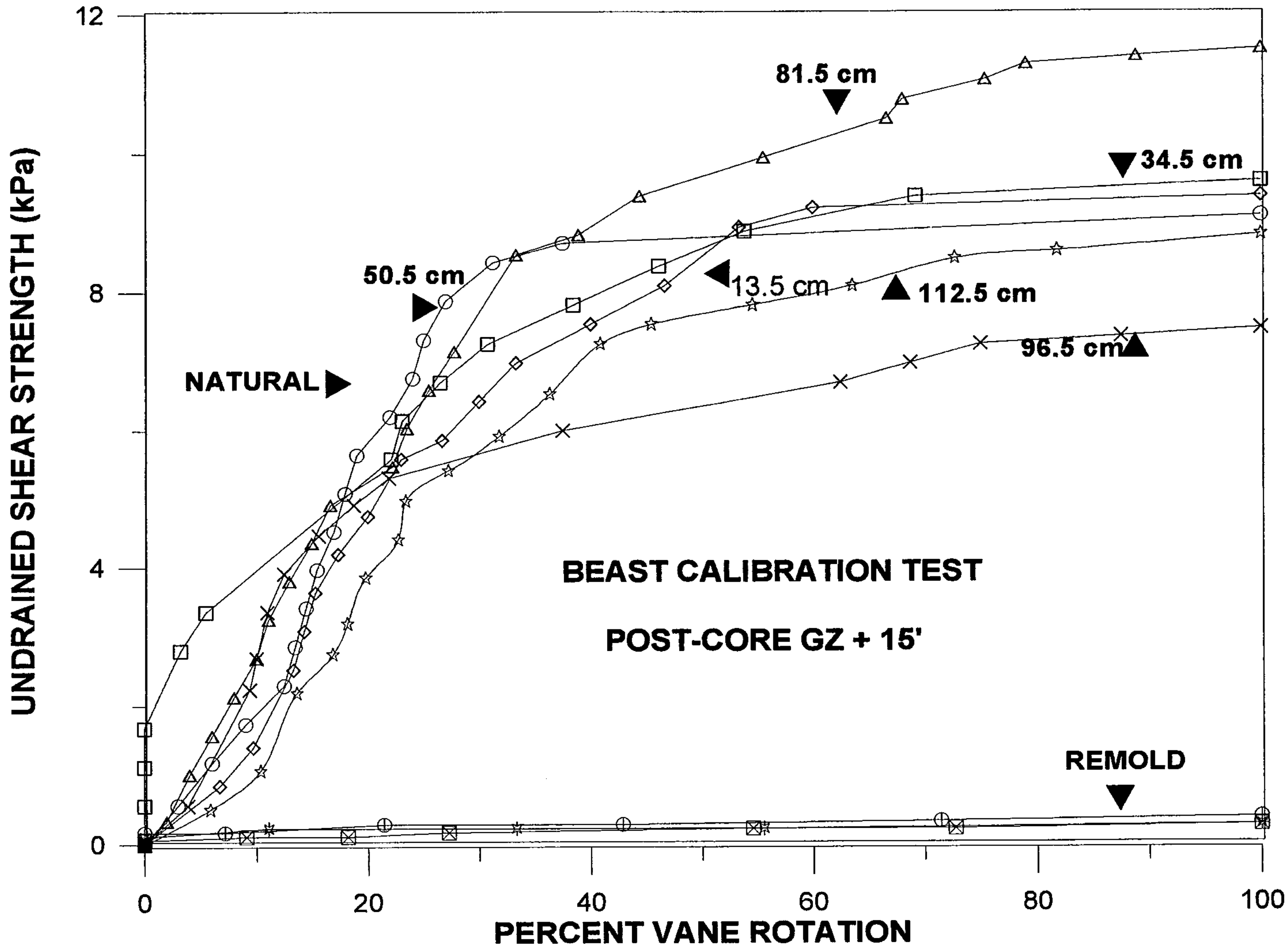


Figure 19. Plot of percent vane rotation versus undrained shear strength for both the natural and the remold state of the material.

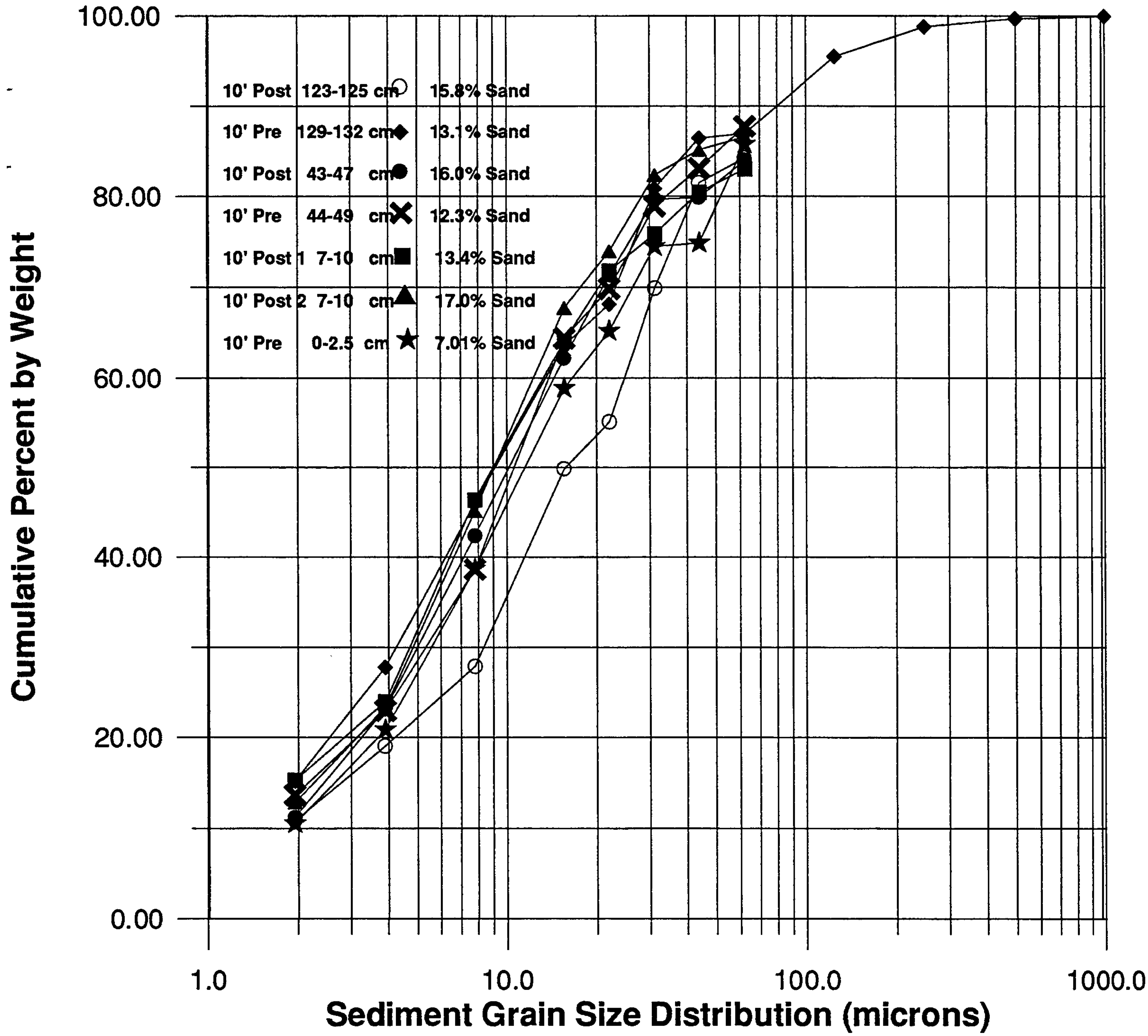


Figure 20. Plot of cumulative grain size distribution from 3 pre and 3 post samples from core at 10 ft. range from GZ.

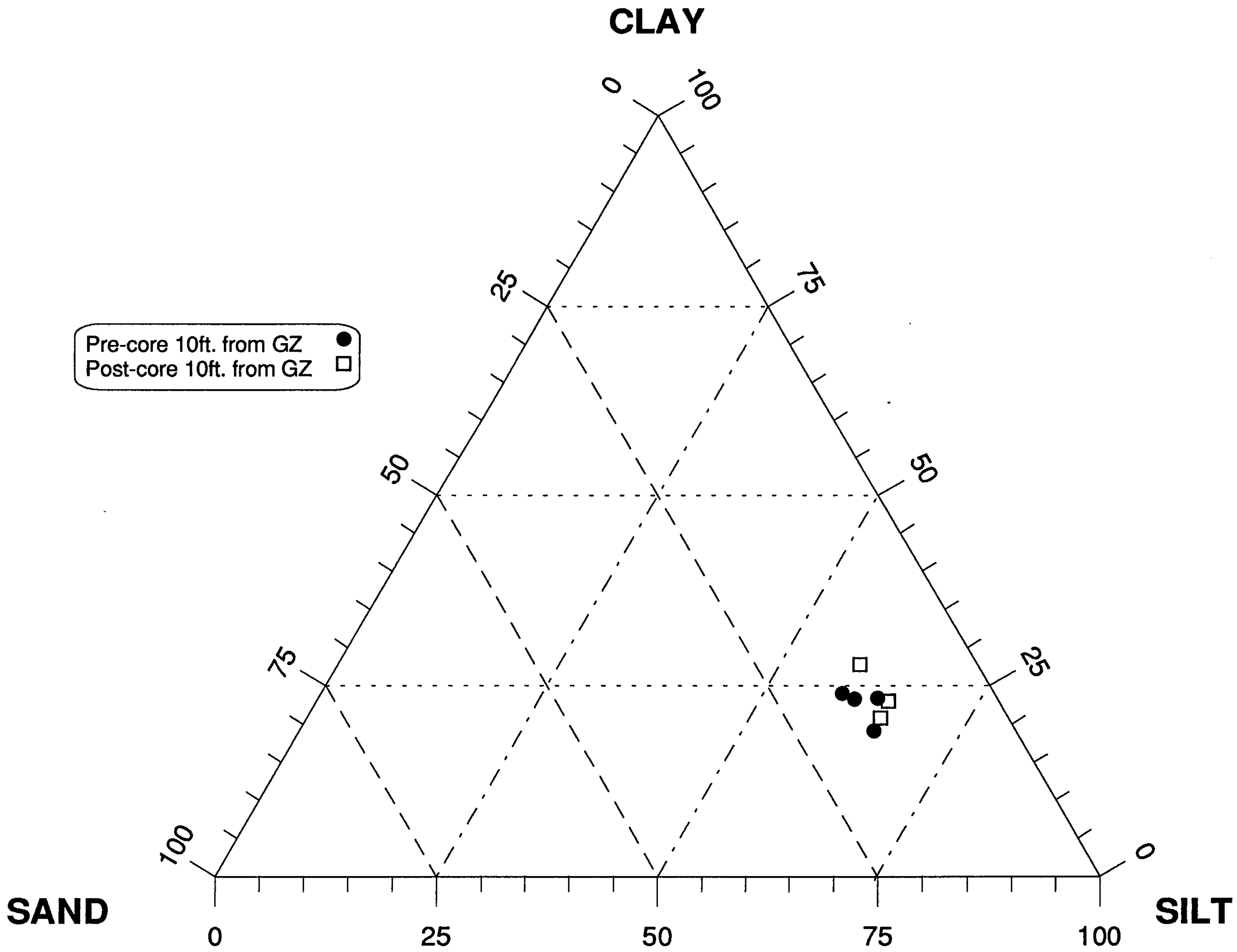


Figure 21. **Ternary diagram depicting plots of % sand, silt, and clay from 3 pre-cores and 4 post cores from 10 ft. range from GZ.**

Comparison of % Gas Estimations Generated by Varying the Average Grain Density

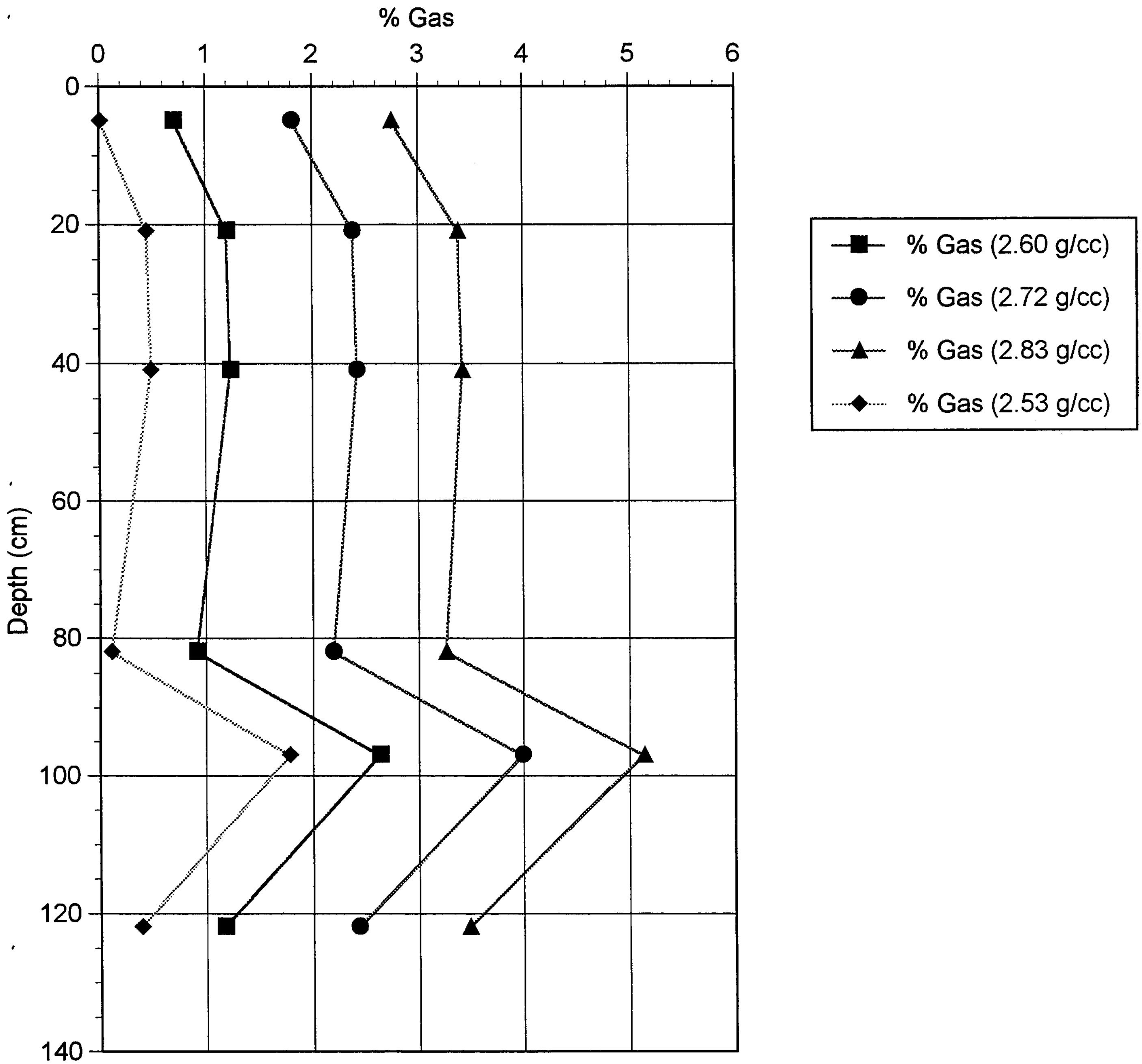


Figure 22: % Gas
BEAST Calibration Test Data
Big Black Test Site
April 1995

Comparison of Percent Saturation Estimations Generated by Varying the Average Grain Density

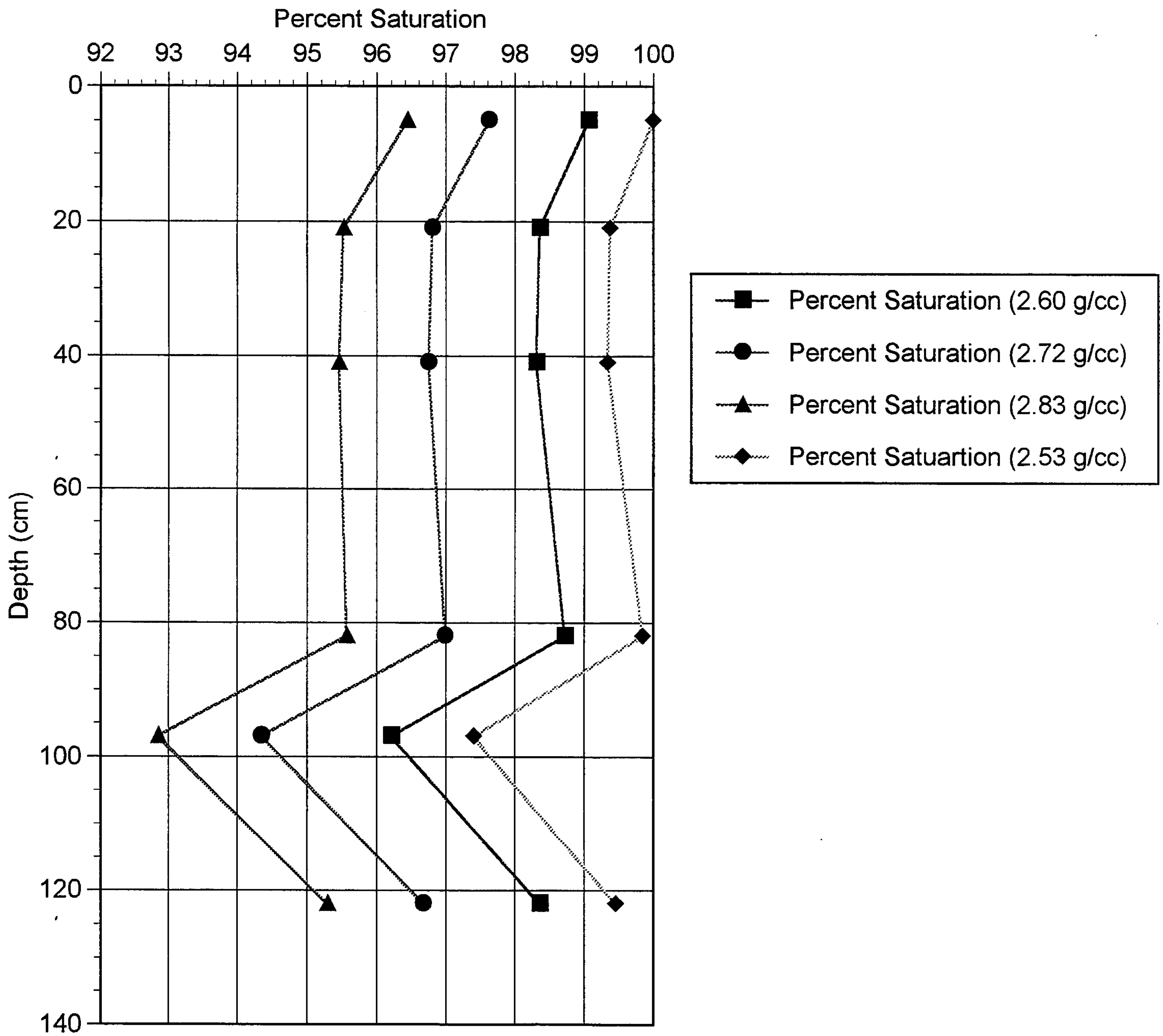


Figure 23: Percent Saturation
BEAST Calibration Test
Big Black Test Site
April 1995

Comparison of Porosity Estimations Generated by Varying the Average Grain Density

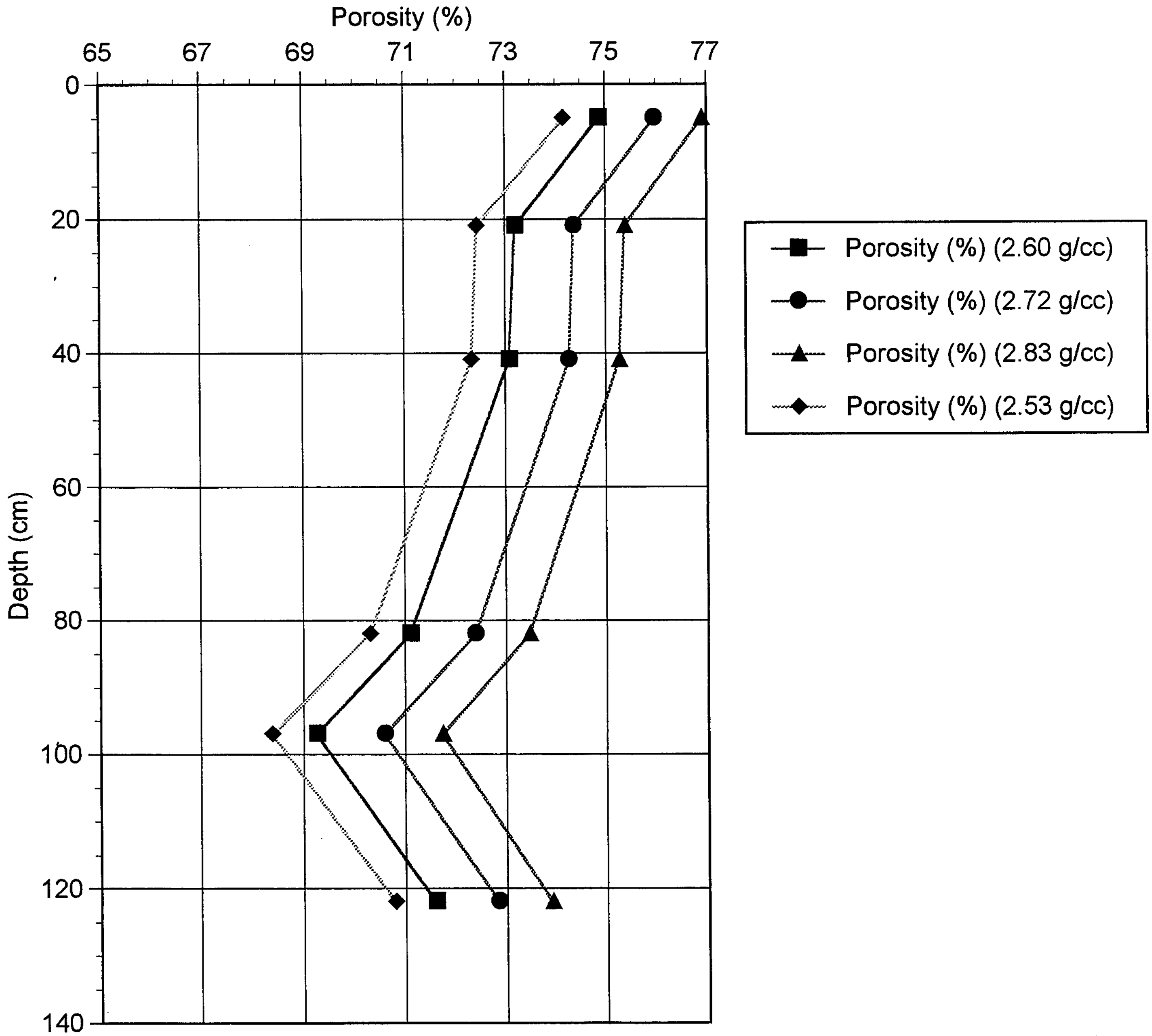


Figure 24: Porosity (%)
BEAST Calibration Test
Big Black Test Site
April 1995

Comparison of Void Ratio Estimations Generated by Varying the Average Grain Density

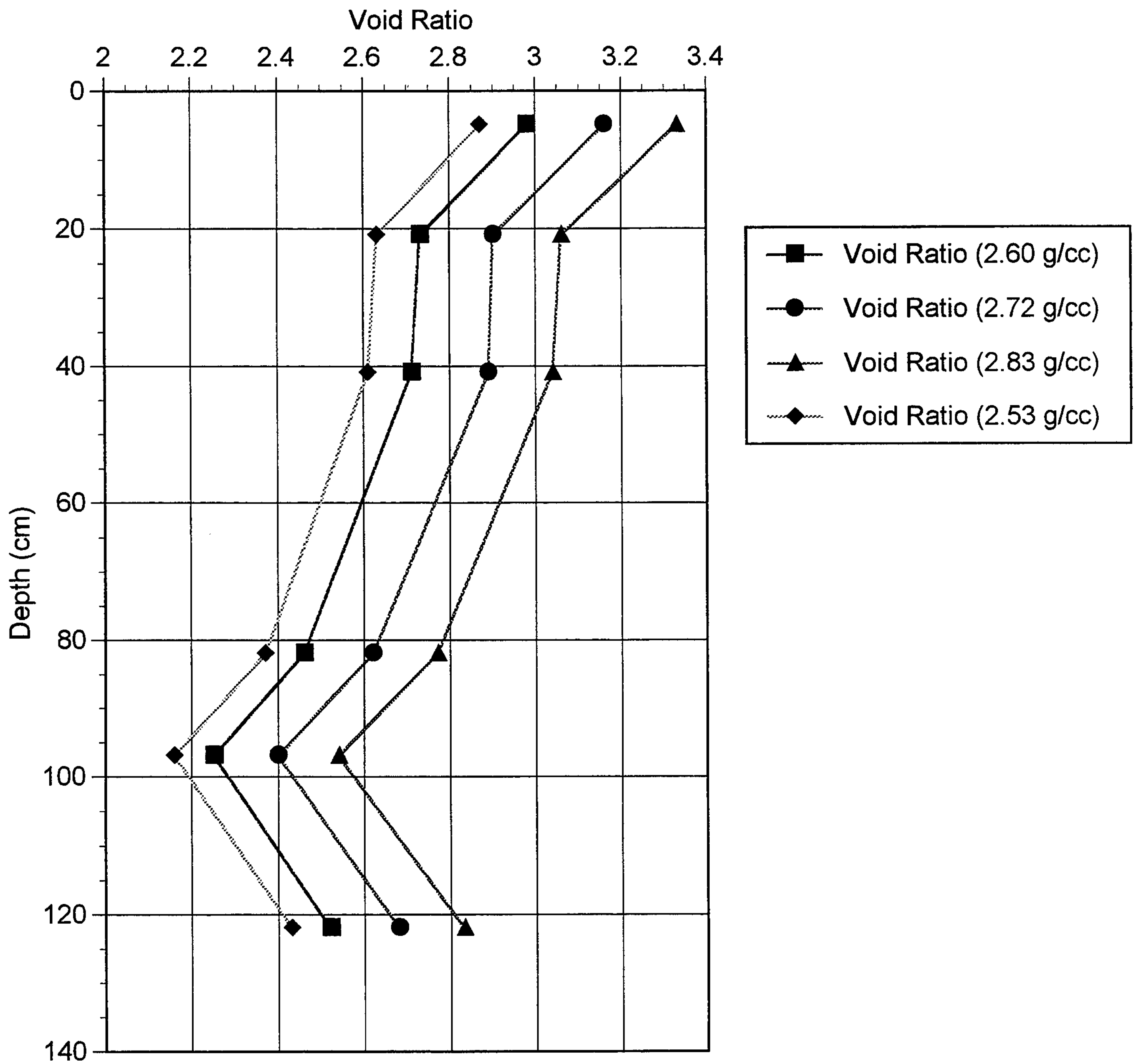


Figure 25: Void Ratio
BEAST Calibration Test
Big Black Test Site
April 1995

Naval Research Laboratory
Statistical Analysis
of Combined Pre- and Post- Shot Data
BEAST Calibration Test
April 1995

Percent Gas		Percent Saturation		Wet Bulk Density (g/cc)			
Mean	1.16	Mean	98.40	Mean	1.44		
Median	0.93	Median	98.71	Median	1.44		
Standard Deviation	0.76	Standard Deviation	1.06	Standard Deviation	0.02		
Variance	0.57	Variance	1.11	Variance	0.00		
Range	3.24	Range	4.45	Range	0.08		
Minimum	0.07	Minimum	95.45	Minimum	1.39		
Maximum	3.31	Maximum	99.90	Maximum	1.47		
Porosity (%)		Void Ratio		Water Content (%dry weight)		Cohesion (kPa)	
Mean	72.28	Mean	2.61	Mean	100.79	Mean	6.81
Median	72.28	Median	2.61	Median	98.84	Median	6.90
Standard Deviation	0.97	Standard Deviation	0.13	Standard Deviation	9.30	Standard Deviation	2.78
Variance	0.94	Variance	0.02	Variance	86.50	Variance	7.70
Range	5.62	Range	0.75	Range	54.23	Range	11.51
Minimum	69.60	Minimum	2.29	Minimum	80.43	Minimum	0.78
Maximum	75.22	Maximum	3.04	Maximum	134.66	Maximum	12.29

Table 1: Values for all samples, pre- and post- shot based on an average grain density of 2.63 g/cc.

Naval Research Laboratory
Statistical Analysis
of Geotechnical Data
Pre- and Post- Detonation
BEAST Calibration Test
April 1995

Percent Air				Porosity			
Pre Shot		Post Shot		Pre Shot		Post Shot	
Mean	1.68	Mean	0.91	Mean	72.43	Mean	72.21
Median	1.50	Median	0.82	Median	72.32	Median	72.21
Standard Deviation	0.96	Standard Deviation	0.49	Standard Deviation	1.48	Standard Deviation	0.64
Variance	0.93	Variance	0.24	Variance	2.18	Variance	0.41
Range	2.89	Range	1.85	Range	5.63	Range	2.65
Minimum	0.41	Minimum	0.07	Minimum	69.60	Minimum	70.91
Maximum	3.31	Maximum	1.92	Maximum	75.22	Maximum	73.56
Percent Saturation				Void Ratio			
Pre Shot		Post Shot		Pre Shot		Post Shot	
Mean	97.67	Mean	98.74	Mean	2.62	Mean	2.61
Median	97.94	Median	98.86	Median	2.58	Median	2.61
Standard Deviation	1.36	Standard Deviation	0.68	Standard Deviation	0.19	Standard Deviation	0.06
Variance	1.84	Variance	0.46	Variance	0.04	Variance	0.00
Range	3.97	Range	2.58	Range	0.75	Range	0.24
Minimum	95.45	Minimum	97.32	Minimum	2.29	Minimum	2.48
Maximum	99.43	Maximum	99.90	Maximum	3.04	Maximum	2.72
Wet Bulk Density (g/cc)				Water Content (%dry)			
Pre Shot		Post Shot		Pre Shot		Post Shot	
Mean	1.43	Mean	1.44	Mean	100.19	Mean	101.26
Median	1.43	Median	1.44	Median	98.74	Median	98.99
Standard Deviation	0.02	Standard Deviation	0.01	Standard Deviation	10.02	Standard Deviation	8.75
Variance	0.00	Variance	0.00	Variance	100.40	Variance	76.51
Range	0.07	Range	0.05	Range	54.23	Range	35.31
Minimum	1.39	Minimum	1.42	Minimum	80.43	Minimum	86.41
Maximum	1.47	Maximum	1.47	Maximum	134.66	Maximum	121.73

Table 2: Values for all Pre- and Post- Shot Data based on an average grain density of 2.63 g/cc.

Naval Research Laboratory
Statistical Analysis
of Geotechnical Data
Pre- Detonation
BEAST Calibration Test
April 1995

Cohesion (kPa)				
Post Shot				
Mean	7.82			
Median	7.60			
Standard Deviation	2.44			
Variance	5.93			
Range	11.01			
Minimum	1.28			
Maximum	12.29			
Percent Gas			Porosity (%)	
Post Shot			Post Shot	
Mean	0.91		Mean	72.21
Median	0.82		Median	72.21
Standard Deviation	0.49		Standard Deviation	0.64
Variance	0.24		Variance	0.41
Range	1.85		Range	2.65
Minimum	0.07		Minimum	70.91
Maximum	1.92		Maximum	73.56
Percent Saturation			Void Ratio	
Post Shot			Post Shot	
Mean	98.74		Mean	2.61
Median	98.86		Median	2.61
Standard Deviation	0.68		Standard Deviation	0.06
Variance	0.46		Variance	0.00
Range	2.58		Range	0.24
Minimum	97.32		Minimum	2.48
Maximum	99.90		Maximum	2.72
Wet Bulk Density (g/cc)			Water Content (%dry)	
Post Shot			Post Shot	
Mean	1.44		Mean	101.26
Median	1.44		Median	98.99
Standard Deviation	0.01		Standard Deviation	8.75
Variance	0.00		Variance	76.51
Range	0.05		Range	35.31
Minimum	1.42		Minimum	86.41
Maximum	1.47		Maximum	121.73

Table 3: Values for all Post- Shot Data based on an average grain density of 2.63 g/cc.

Naval Research Laboratory
Statistical Analysis

Shear Strength Data
BEAST Calibration Test
April 1995

Undrained Shear Strength (kPa)					
10 Pre Shot				15 Pre Shot	
Mean	3.51	12.5 Pre Shot		Mean	7.52
Median	3.80	Not Available		Median	7.68
Standard Deviation	1.73			Standard Deviation	1.53
Variance	2.99			Variance	2.34
Range	5.92			Range	4.25
Minimum	0.78			Minimum	5.08
Maximum	6.70			Maximum	9.33
10 Post Shot		12.5 Post Shot		15 Post Shot	
Mean	6.77	Mean	7.63	Mean	9.32
Median	6.42	Median	7.71	Median	9.24
Standard Deviation	1.37	Standard Deviation	3.23	Standard Deviation	1.31
Variance	1.88	Variance	10.41	Variance	1.70
Range	4.14	Range	11.01	Range	4.02
Minimum	5.53	Minimum	1.28	Minimum	7.48
Maximum	9.67	Maximum	12.29	Maximum	11.50

Table 4: Undrained Shear Strength (kPa).

Naval Research Laboratory
Statistical Analysis

Water Content (%dry weight) Data
BEAST Calibration Test
April 1995

10 Pre Shot				15 Pre Shot	
Mean	102.47	12.5 Pre Shot		Mean	97.69
Median	102.50	Not Available		Median	97.79
Standard Deviation	13.33			Standard Deviation	2.78
Variance	177.77			Variance	7.73
Range	54.23			Range	11.56
Minimum	80.43			Minimum	92.19
Maximum	134.66			Maximum	103.75
10 Post Shot		12.5 Post Shot		15 Post Shot	
Mean	108.34	Mean	96.81	Mean	97.00
Median	110.91	Median	96.35	Median	97.92
Standard Deviation	9.30	Standard Deviation	5.30	Standard Deviation	3.76
Variance	86.45	Variance	28.05	Variance	14.17
Range	30.24	Range	22.72	Range	13.84
Minimum	91.49	Minimum	86.41	Minimum	88.65
Maximum	121.73	Maximum	109.13	Maximum	102.49

Table 5: Water Content (%dry weight) Data

Naval Research Laboratory
Statistical Analysis

Percent Saturation Data
BEAST Calibration Test
April 1995

10 Pre Shot				15 Pre Shot	
Mean	97.74	12.5 Pre Shot		Mean	97.57
Median	97.94	Not Available		Median	97.71
Standard Deviation	1.03			Standard Deviation	1.93
Variance	1.07			Variance	3.72
Range	2.95			Range	3.98
Minimum	95.72			Minimum	95.45
Maximum	98.67			Maximum	99.43
10 Post Shot		12.5 Post Shot		15 Post Shot	
Mean	98.61	Mean	98.57	Mean	99.04
Median	98.63	Median	98.84	Median	99.04
Standard Deviation	0.85	Standard Deviation	0.70	Standard Deviation	0.44
Variance	0.73	Variance	0.49	Variance	0.20
Range	2.35	Range	2.03	Range	1.39
Minimum	97.55	Minimum	97.32	Minimum	98.33
Maximum	99.90	Maximum	99.35	Maximum	99.72

Table 6: Percent Saturation Data based on an average grain density of 2.63 g/cc.

Naval Research Laboratory
Statistical Analysis

Percent Gas Content Data
BEAST Calibration Test
April 1995

10 Pre Shot				15 Pre Shot	
Mean	1.63			Mean	1.76
Median	1.50	12.5 Pre Shot		Median	1.65
Standard Deviation	0.70	Not Available		Standard Deviation	1.40
Variance	0.49			Variance	1.97
Range	2.03			Range	2.90
Minimum	0.95			Minimum	0.41
Maximum	2.98			Maximum	3.31
10 Post Shot		12.5 Post Shot		15 Post Shot	
Mean	1.00	Mean	1.03	Mean	0.69
Median	0.98	Median	0.83	Median	0.69
Standard Deviation	0.62	Standard Deviation	0.50	Standard Deviation	0.32
Variance	0.38	Variance	0.25	Variance	0.10
Range	1.70	Range	1.45	Range	0.98
Minimum	0.07	Minimum	0.47	Minimum	0.21
Maximum	1.77	Maximum	1.92	Maximum	1.19

Table 7: Percent Gas Data based on an average grain density of 2.63 g/cc.

Wet Bulk Density (g/cc)
BEAST Calibration Test
April 1995

10 Pre Shot				15 Pre Shot	
Mean	1.43	12.5 Pre Shot		Mean	1.43
Median	1.43	Not Available		Median	1.44
Standard Deviation	0.03			Standard Deviation	0.02
Variance	0.00			Variance	0.00
Range	0.08			Range	0.04
Minimum	1.39			Minimum	1.41
Maximum	1.47			Maximum	1.45
10 Post Shot		12.5 Post Shot		15 Post Shot	
Mean	1.44	Mean	1.44	Mean	1.45
Median	1.44	Median	1.44	Median	1.45
Standard Deviation	0.02	Standard Deviation	0.01	Standard Deviation	0.01
Variance	0.00	Variance	0.00	Variance	0.00
Range	0.05	Range	0.03	Range	0.02
Minimum	1.42	Minimum	1.43	Minimum	1.43
Maximum	1.47	Maximum	1.46	Maximum	1.45

Table 8: Wet Bulk Density (g/cc) Data

Naval Research Laboratory
Statistical Analysis

Porosity (%) Data
BEAST Calibration Data
April 1995

10 Pre Shot				15 Pre Shot	
Mean	72.49	12.5 Pre Shot		Mean	72.33
Median	72.65	Not Available		Median	72.32
Standard Deviation	1.96			Standard Deviation	0.31
Variance	3.85			Variance	0.10
Range	5.62			Range	0.76
Minimum	69.60			Minimum	71.95
Maximum	75.22			Maximum	72.71
10 Post Shot		12.5 Post Shot		15 Post Shot	
Mean	72.17	Mean	72.29	Mean	72.16
Median	72.03	Median	72.44	Median	72.21
Standard Deviation	0.91	Standard Deviation	0.57	Standard Deviation	0.53
Variance	0.82	Variance	0.33	Variance	0.28
Range	2.65	Range	1.88	Range	1.60
Minimum	70.91	Minimum	71.26	Minimum	71.44
Maximum	73.56	Maximum	73.14	Maximum	73.04

Table 9: Porosity (%) Data based on an average grain density of 2.63 g/cc.

Naval Reserch Laboratory
Statistical Analysis

Void Ratio Data
BEAST Calibration Test
April 1995

10 Pre Shot				15 Pre Shot	
Mean	2.65	12.5 Pre Shot		Mean	2.62
Median	2.66	Not Available		Median	2.62
Standard Deviation	0.26			Standard Deviation	0.04
Variance	0.07			Variance	0.00
Range	0.75			Range	0.09
Minimum	2.29			Minimum	2.57
Maximum	3.04			Maximum	2.66
10 Post Shot		12.5 Post Shot		15 Post Shot	
Mean	2.60	Mean	2.61	Mean	2.59
Median	2.58	Median	2.63	Median	2.60
Standard Deviation	0.12	Standard Deviation	0.07	Standard Deviation	0.07
Variance	0.01	Variance	0.01	Variance	0.00
Range	0.34	Range	0.24	Range	0.21
Minimum	2.44	Minimum	2.48	Minimum	2.50
Maximum	2.78	Maximum	2.72	Maximum	2.71

Table 10: Void Ratio Data based on an average grain density of 2.63 g/cc.

CORE 10 PRE- SHOT					
	Tube #	Depth (cm)	WES GRAIN DENSITY	NRL GRAIN DENSITY gently ground by hand	NRL GRAIN DENSITY throughly ground by mortar and pestle
	42	5	2.63	2.65	2.77
				2.66	
				2.69	
	19	41	2.63	2.77	2.70
				2.72	
	34	97	2.63	2.69	2.83
				2.73	
	6	122	2.63	2.75	2.94
				2.70	
CORE 10 POST- SHOT					
	Tube #	Depth (cm)	WES GRAIN DENSITY	NRL GRAIN DENSITY gently ground by hand	NRL GRAIN DENSITY ground by mortar and pestle
	35	15	2.63	2.63	2.87
				2.75	
				2.77	
	21	52	2.63	2.60	2.85
				2.64	
	53	88	2.63	2.66	2.74
				2.70	
				2.74	
	14	117	2.63	2.82	2.84
				2.82	

Table 11: Comparison of Average Grain Density (g/cc) Data Generated By Different Disaggregating Methods

APPENDIX A:

FLY ASH CHARACTERISTICS

The original objective was to select a material that would simulate a shallow-water marine sedimentary deposit. A straightforward rationale led to the selection of grout as the material for the BEAST testbed. That was, since the composition of the grout was believed to be precisely controllable, the geotechnical properties of the testbed could be closely predetermined. This approach capitalizes on the Corps of Engineers' vast experience with grouts in a variety of scenarios, but it turns out that it leaves open one unexpected opportunity for problems to enter.

A major component of the grout is fly ash, and unfortunately it turns out that the properties of fly ash can vary rather widely depending on the processes involved in its derivation and capture. The two most common activities leading to the formation of fly ash are the generation of steam for power generation or manufacturing, and the treatment of solid waste in municipal waste combustors. In both processes, coal is commonly used, and temperatures can reach more than 1800 degrees F. To scrub sulphur dioxide and other pollutants and render the residue more compact, water and lime (CaO) are generally added along the way. The fluxing properties of lime and water promote the formation of glasses at such temperatures.

While there are some differences, fly ashes formed during both processes mentioned above have many similarities. Both are comprised mostly of silica, alumina, and iron oxide that have reacted/interacted in the presence of lime, water, and (usually) sulphur dioxide. To quote R.W. Goodwin (COMBUSTION ASH/RESIDUE MANAGEMENT: An Engineering Perspective): "Lime (CaO) in the presence of silica (SiO2), alumina (Al2O3), and iron oxide (Fe2O3) forms sulfo-alumina hydrates (ettringites) and calcium silica hydrate (toberite), [which are] pozzolanic end products." Depending on its source and treatment, end-product pH can range from about 7 to at least 11. There is often additional treatment to obtain commercial fly ash suitable for specific applications.

All of the above implies that fly ash tends to be glassy and reactive and that it will have long-term curing characteristics: or as noted above, it is "pozzolanic." This also suggests it may be more like the volcanic (leucite) tuff of Pozzuoli, Italy, where the name for the reaction arose, than marine sediments laid down in very different environments. Of course, lime, sulphur, and water can also react to yield gypsum, with its Plaster-of-Paris properties.

Additional information and analyses of the fly ash used in the BEAST testbed were gathered using points of contact provided by Don Walley of the WES. The material used in th BEAST testbed comes from Arkansas Power and Light Company's (AP&L) sub-bituminous coal fired White Bluff Power Plant in Redfield, Arkansas. Barry Snow, AP&L's chemist, stated that AP&L uses coal from Wyoming by the trainload, powdering it to 300 mesh screen size and burning it at 2200°F in 10-story-high tangentially fired pulverized coal boilers.

This low-grade coal typically leaves about 30% of its weight in solid residue. Sulphur content in this particular coal is so low that AP&L meets Environmental Protection Agency standards without stack scrubbing. The fly ash is derived entirely from the coal. Specifically, they do not have to add lime or other additives to the combustion products. They simply catch the fly ash with the electrostatic precipitators and sell it. Incidentally, the ash is in high demand by the cement industry, who uses it as a physical property enhancement additive to Portland and other cements.

The 2200°F furnace temperature is hot enough to sinter or fuse most earthly inclusions in the coal into pumice-like glass beads of complex calcium aluminosilicates, ferrite spinels, and other igneous rock-like products, a fraction of which are vesicular. This agrees with what we observe under the microscope. According to Snow, Dr. Marvin Dudas of the University of Alberta has studied and published extensively on both this fly ash and the ash from the Mount Saint Helens volcanic eruption. He finds a "remarkable similarity" between them.

APPENDIX B:

LABORATORY METHODOLOGY AND TECHNIQUES

LABORATORY METHODOLOGY AND TECHNIQUES

Sediment Shear Strength

Shear Strength Testing

The process of shear in clays and silty clays is complex. Sediments are composed of a variety of particle sizes and these particles must slide or rotate for the shear to take place. The skeleton or frame forces acting on the soil are a function of the stress normal to the shear plane carried by the clay particles. The vane shear test is used to determine the maximum shearing resistance or cohesion for a given sample of clay in an undrained condition. This test is used for the in situ or laboratory determination of the undrained strength of fully saturated clays.

Let:

c = cohesion
σ = total normal stress
μ = pore pressure
σ' = $\sigma - \mu$ = "effective stress"
ϕ = angle of shearing resistance

Then shearing resistance on a plane at failure, τ_f, can be expressed by:

$$\tau_f = c + \sigma' \tan \phi. \tag{1}$$

When soil is stressed without loss of pore water, σ is equal to μ and σ' is zero, and:

$$\tau_f = c.$$

The stainless steel vane consists of four thin rectangular blades carried on the end of a steel rod. The vane and the rod are inserted into the clay with minimal disturbance, then torque is applied at a rate of 70 - 90^{o}/min until the clay fails in shear (Richards, 1961).

Mass Physical Properties

Water Content

Water content (w) is the ratio of the mass or weight of the water (M_W) to the mass or weight of the solids (M_S) in the soil. It is usually expressed in percent:

$$w = (M_W / M_S) * 100. \tag{2}$$

The sediment water content was determined by weighing a wet sample of the sediment and then drying the sample in an oven at a temperature of 105^{o}C, then reweighing (Lambe, 1951). The normal drying period was 24 hours. Salt corrections to the physical properties are routinely made for a measured pore water salinity in marine sediments; however, results of salinity measurements run on the grout material pore water were ~zero ^{o}/oo (parts per thousand) and, therefore, salt corrections were not required.

Degree of Saturation

The degree of saturation (S) is the ratio of the volume of water (V_W) to the total volume of void space (V_V):

$$S = V_W / V_V * 100. \tag{3}$$

Degree of saturation, like water content, is usually reported as a percentage. The volume of the voids in a given sediment mass is subject to variation and the water content of a soil may change, but the degree of saturation could remain constant, e.g., marine sedments may have the same value for saturation but have highly variable and different water contents. As is seen in clays, a soil can reach 100% saturation especially in deep-water marine environments. The degree of saturation can be related to the total gas content of a soil mass as follows:

$$\% \text{ Gas} = [(1-S) * n] * 100\%. \tag{4}$$

(Note: Use decimal equivalents for S and n, porosity)

Percent Gas

Percent gas is defined as the ratio of the volume of gas (V_g) to the total volume (V_t) :

$$\% \text{ gas} = V_g / V_t = (V_v - V_w) / V_t * 100\%,$$

where $V_t = V_v / n =$ tube volume $= V_v + V_s$

$$V_v = V_t - V_s \quad (5)$$

V_s = (dry sediment weight) / G_s.

Note: G_s = average grain density
n = porosity
V_v = volume of voids
V_s = volume of solids.

Percent gas was determined in the laboratory using precision volumetric tubes (each having a known volume); therefore, absolute values of gas content may be more meaningful than percent saturation values for computational modeling requirements. Again, corrections for pore water salinity were not applied to the calculations because the pore water salinity was zero or very close to zero.

Wet Unit Weight

The wet unit weight (γ_t), or wet bulk density, is the ratio of the weight or mass (W) of the sediment to the total volume (V_t):

$$\gamma_t = W / V_t . \quad (6)$$

The wet unit weight (or wet bulk density) is a weight per unit volume which was determined by inserting a tube of known volume into a sediment mass, extracting the tube with the sample, and determining the sediment weight or mass in grams. This procedure yields a mass (gm) per unit volume.

Porosity

The porosity (n) of a sediment is the ratio of the pore space to the total volume of a soil mass, or more simply, the ratio times 100 of the volume of the voids (V_v) to the total volume (V_t) of the sediment mass. The porosity of a sediment is largely governed by the uniformity of grain size, the shape of the grains, the processes during and after deposition (consolidation/dewatering), and the spatial distribution of the sediment particles (Bennett et al., 1977). For our purposes, porosity was determined from the wet weight, tube volume, average grain density, dry weight, and water content using precision calibrated tubes:

$$n = V_v / V_t. \tag{7}$$

Void Ratio

The void ratio (e) is defined as the volume of the voids (V_v) to the volume of the solids (V_s), where $e = V_v / V_s$. Porosity and void ratio are related as follows:

$$n = e / 1 + e. \tag{8}$$

Average Grain Density

Average grain density was determined by NRL from dried, powdered samples using a gas pycnometer. The pycnometer is designed to determine the volume of solid objects. Volume in a pycnometer is determined through the use of Archimedes principle of fluid displacement. In our case, the fluid used is a gas (helium), thereby ensuring complete penetration of the pore spaces and yielding a high degree of accuracy and precision. Given the volume and mass of a given powder, the average grain density (g/cc) is calculated. (*The grout mixture was found to exhibit a high degree of variability and uncertainty in average grain density; see details in the section on grain density measurements.)*

Atterberg Limits

The primary purpose of the Atterberg Limits is to serve as indices and classification of the significant properties of sediments (soils) (Table 1). The liquid limit has been found to have a direct proportionality to the compressibility of soil and the plasticity index (the difference between the liquid and plastic limits) represents the range of water contents through which the soil is in a plastic state. Surficial fine-

grained marine sediments are highly compressible. Basically, the limits refer to boundaries between the soil states, such as liquid, plastic, and solid.

TABLE 1 - Atterberg Limits (Sowers and Sowers, 1951; revised 1961)

Soil State	**Description**	**Boundary**
Liquid Limit	a slurry, pea soup to soft butter, a viscous liquid	
		Liquid
Plastic Limit	soft butter to stiff putty, deforms but will not crack	
		Plastic
Semisolid Limit	cheese, deforms permanently but cracks	
		Shrinkage
Solid	hard candy, fails completely upon deformation	

Precision of Techniques

Equations for the calculations of the various mass properties studied are found in textbooks on soil mechanics, e.g., Lambe (1951), Sowers and Sowers (1951; 1961), and Terzaghi and Peck (1967).

Test procedures for the mass physical properties closely followed methods described by Lambe (1951) and the American Society for Testing Materials (ASTM) (1958). Cohesion was determined using a laboratory vane shear apparatus following the procedures outlined by Richards (1961) for marine sediments. Published reports on the precision of the laboratory vane shear apparatus are few. Richards (1964) reported a precision of approximately 0.69 kPa for vane shear tests. Kenney and Landva (1965) reported a reproducibility of ±1% over the entire torque range for their laboratory vane-triaxial apparatus. The vane apparatus used in this study is marked in 1^{o} divisions of rotation with an estimated readability of 0.25^{o}. A 1.3-cm x 2.54-cm vane and one of four calibrated springs are commonly used depending upon the strength of the material. In this study the weakest spring was used for all measurements due to the low torque values required to cause shear failure of the vane within the grout. In terms of cohesion, a reproducibility of 0.02 to 0.08 kPa is achieved depending on the spring used. The authors consider the latter figures a reasonable estimate of the precision of the laboratory vane shear apparatus.

Sand, silt, and clay fractions were determined by sieving and settling analyses. Bader (1957) stated that the average reproducibility for a given size grade determination was ±0.2% and that differences in analyses greater than ±0.4% probably represent actual sample variations. Variations greater than this are considered as representing natural variations in the properties and in the size fractions rather than reflecting differences in analytical technique.

Although no rigorous calibration was made of the balance used to determine water content, wet unit weight, and average grain density measurements, values greater than ±0.01% of the observed values for water content, wet unit weight, and ±0.5% for average grain density are considered to reflect natural variations among the samples. These values are considered a reasonable estimate of the reproducibility (precision) and greater refinement would lack practical significance.

Because of the very short time involved, loss of water through evaporation from the time of extracting the sample in the laboratory to its weighing is considered negligible. Differences and absolute values were of importance in this study, and careful and consistent techniques were used to ensure a uniform testing procedure.

Void ratio and porosity were computed from water content, precision tube volumes, and specific gravity (average grain density) values and would be subject to any error in these basic properties. In an earlier study, a few simple computations revealed that void ratio was in error by less than ±2% and porosity by less than ±1% of the observed values (Bennett et al.., 1970) given reliable values for average grain density.

The average precision of the tube volumes used for percent gas calculations is ± 0.01 cc with maximum values of ± 0.04 cc. The volume of the tubes averaged 170.51 cc. Thus, the precision of the tubes is an order of magnitude better than the reported values for percent gas. The reader is refered to a comprehensive discussion of the precision of techniques in geotechnical analyses in Bennett et al., (1970).

APPENDIX C:

NRL Letter to U.S. Army Corp of Engineers with Enclosed Tables of Marine Geotechnical Index Properties from Patuxent River/Chesapeake Bay

DEPARTMENT OF THE NAVY
NAVAL RESEARCH LABORATORY
STENNIS SPACE CENTER, MISSISSIPPI 39529-5004

IN REPLY REFER TO

3910
Ser 7430/28
July 29,1994

U.S. Army Corp of Engineers
Waterways Experiment Station
CEWES-SD (John Ehrgott)
3909 Halls Ferry Road
Vicksburg, MS 39180

Dear Mr. Ehrgott:

Pursuant to our meeting at the Naval Research Laboratory (NRL) on June 21, 1994 (John Ehrgott, Max Ford, Lafe Maynard, Dick Faas, Nancy Hunter, and Dick Bennett), NRL agreed to provide estimates of the expected geotechnical properties for selected coastal environments based on data currently available in our files. The attached table summarizes the data from coastal environments. We are presently compiling a comprehensive data base on the geotechnical properties of numerous coastal environments and additional information will be available near the end of this summer.

We are providing a preliminary summary of properties for four sediment (soil) types of interest for establishing criteria for the planned test bed.

The data are provided for sandy mud, clayey silt, silty clay, and sandy silt following the textural classification of Shepard, 1954.

Other enclosures contain tables and graphs on the Big Black test site samples.

Sincerely,

Richard H. Bennett
Senior Research Oceanographer

Copy to:
M. Ford
D. Bruder
J. Goertner
H. Olsen

Values of Sediment Geotechnical Properties for Selected Area of the Patuxent River (Second Cove): data from NAVOCEANO Report

The following are statistical data sets presented for four discrete classes of recent sediments from Chesapeake Bay. They are classified according to Shepard (1954) and represent the most commonly occurring sediment types for which data are available.

SECOND COVE, PATUXENT RIVER

Sed. Class	Water Content % dry wt	Wet Bulk Density g/cm^3	Grain Density g/cm^3	Porosity %	Shear Strength kPa
SANDY MUD					
Mean	103.54	1.38	2.52	72.0	7.8
Std Dev.	17.14	0.10	0.08	4.5	5.2
Max	135.21	1.49	2.57	74.1	17.8
Min	72.91	1.19	2.41	70.8	2.8
# of Samples	7	7	5	5	7
CLAYEY SILT					
Mean	126.31	1.36	2.59	75.3	3.8
Std Dev.	26.74	0.15	0.12	3.3	3.6
Max	211.70	1.54	2.68	80.6	21.3
Min	73.31	1.23	2.44	65.9	0.6
# of Samples	42	42	18	18	38
SILTY CLAY					
Mean	165.87	1.29	2.55	81.6	4.6
Std Dev.	35.65	0.15	0.12	2.1	1.5
Max	209.61	1.45	2.71	84.3	7.8
Min	96.62	1.23	2.47	77.2	1.9
# of Samples	25	25	10	10	22

There appears to be a dearth of sandy silt in our data base. The data presented above represent a set of samples collected from different area as follows: St. Andrews Bay, FL (1), Pensacola, FL (2), Lower Chesapeake Bay (1), Pigeon Pt, DE (4), Edgemoor Disposal Site, PA (1).

SANDY SILT					
Mean	65.5	-	-	59.9	-
Std Dev.	56.5	-	-	14.4	-
Max	296.0	-	-	77.2	-
Min	71.5	-	-	34.8	-
# of Samples	9			9	

Compiled by: Dr. R. W. Faas

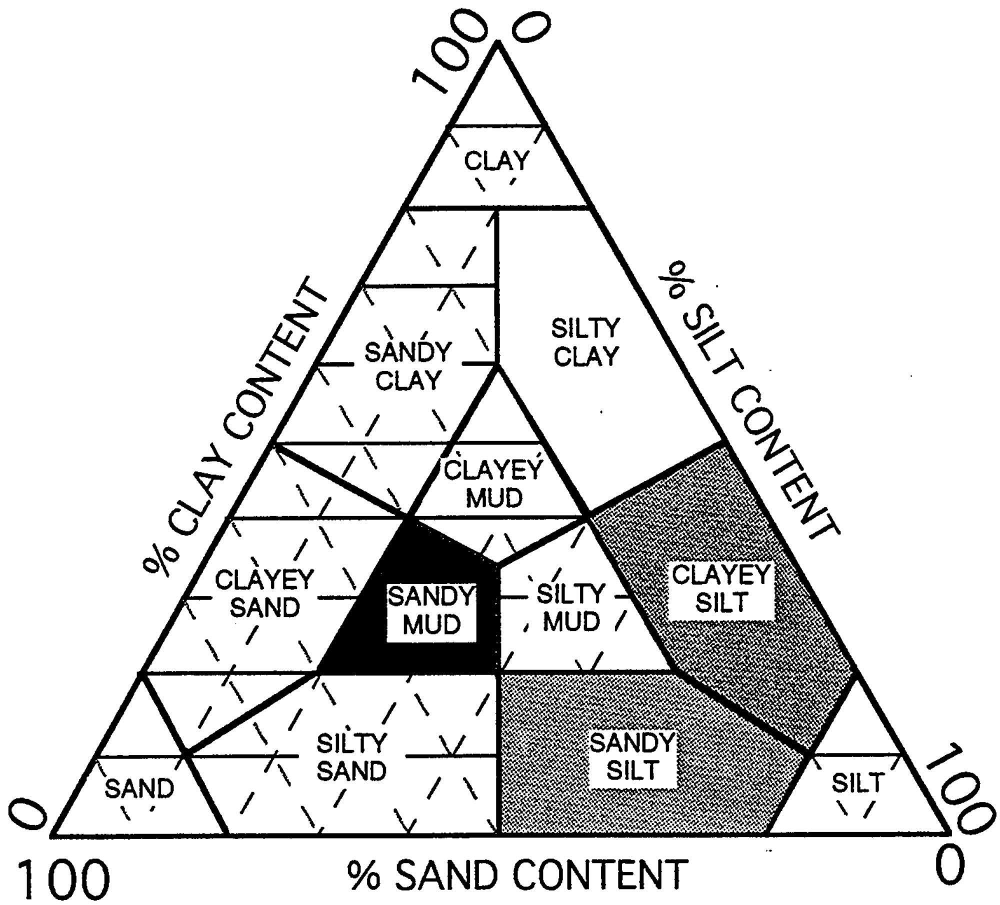
Explanation of the Data

The terms "silty clay", "sandy silt", "sandy mud", etc (Shepard, 1954) are semi-quantitative descriptors which are used to give some meaning to a range of sediment sizes and percentages which are extracted from a size distribution analysis of a naturally occurring marine sediment. Geologists and sedimentologists use the following criteria based upon particle diameter: gravel (>2.00 mm), sand (0.062 mm to 2.00 mm), silt (0.0039 mm to 0.062 mm), clay (<0.0039 mm). This is in conflict with soil engineers who used 0.074 mm to differentiate between sand and silt, and 0.002 mm to differentiate between silt and clay.

It is clear from the ternary diagram (Figure 4) that each descriptor encompasses a range of particle sizes and percentages. The following examples show this:

DESCRIPTOR	COMPOSITION & PERCENTAGE RANGE
Silty clay	Sand - 0 to 20%
	Silt - 10 to 50%
	Clay - 40 to 80%
Clayey silt	Sand - 0 to 20%
	Silt - 10 to 80%
	Clay - 20 to 80%
Sandy silt	Sand - 20 to 50%
	Silt - 40 to 80%
	Clay - 0 to 20%
Sandy mud	Sand - 33 to 60%
	Silt - 20 to 40%
	Clay - 20 to 40%

The range in particle sizes and percentages in each size class is responsible for creating similar variation in those parameters which depend upon particle packing. Thus, the range and standard deviation for water content and porosity is usually quite large, whereas much smaller ranges and standard deviations are observed with bulk (wet) density and grain density which dependent upon the properties of the material.



MODIFIED NOMENCLATURE OF SEDIMENT TYPES
(after Shepard, 1954, p. 157)

Figure 4. Ternary diagram of sediment types.

APPENDIX D:

Table of Marine Geotechnical Index Properties for the Western North Atlantic

(Extracted from Bennett et al., 1980)

Comparison of geotechnical data for four sedimentary provinces of the western North Atlantic mega-corridor and the North Atlantic Ocean Basin

	Water content (%)	Cohesion (kPa)*	Wet unit weight (Mg/m^3)	Porosity (%)	Sand (%)	Silt (%)	Clay (%)
Fluvial-marine: (depths generally less than 3600 m)							
Atlantic slope:							
Max	165	24.1	1.97	82	74	72	74
Min	33	0.9	1.31	44	<1	<1	10
Avg	88	8.3	1.52	71	13	42	44
Upper rise:							
Max	131	13.3	1.69	77	38	49	85
Min	49	2.2	1.39	60	<1	13	22
Avg	94	7.6	1.49	72	7	35	58
Outer Hudson Canyon:							
Max	129	15.7	1.99	76	59	67	78
Min	26	1.8	1.39	42	<1	21	8
Avg	73	5.7	1.60	66	12	38	51
Western Atlantic mega-corridor as a whole (deep-water deposits; depths greater than 2000 m)							
Max	112	17.4	1.94	80	—	—	—
Min	27	2.1	1.39	44	—	—	—
Avg	76	4.8	1.62	65	—	—	—
North Atlantic Ocean Basin							
Max	207	90.7	2.65	85	—	—	—
Min	15	0.1	1.25	32	—	—	—
Avg	86	5.2	1.52	66	—	—	—

Western Atlantic mega-corridor: depths greater than 2000 m

		Water content (%)	Shear strength (kPa)*	Wet unit weight (Mg/m^3)	Porosity (%)
Fluvial-marine (deep water)	Max	102	9.7	1.88	74
	Min	27	2.6	1.46	48
	Avg	70	4.2	1.63	64
Calcareous ooze	Max	112	17.4	1.93	80
	Min	32	2.1	1.43	44
	Avg	75	6.0	1.62	65
"Red clay"	Max	111	5.6	1.94	75
	Min	42	2.6	1.39	54
	Avg	77	4.2	1.66	65

*kPa = $g/cm^2 \times 0.098$ = psi × 6.895.

APPENDIX E:

GEOTECHNICAL PROPERTIES DATA
Grain Density Variability

Naval Research Laboratory
Statistical Analysis
of Geotechnical Data
Post Detonation
BEAST Calibration Test
April 1995

Vol of Solids (cc)		Vol Voids (cc)		Void Ratio		Porosity (%)	
Mean	45.52	Mean	124.92	Mean	2.75	Mean	73.3
Median	45.64	Median	124.53	Median	2.73	Median	73.2
Standard Deviation	1.46	Standard Deviation	1.19	Standard Deviation	0.11	Standard Deviation	0.8
Variance	2.15	Variance	1.42	Variance	0.01	Variance	0.6
Range	3.47	Range	3.20	Range	0.28	Range	2.0
Minimum	43.46	Minimum	123.37	Minimum	2.63	Minimum	72.4
Maximum	46.93	Maximum	126.57	Maximum	2.91	Maximum	74.4
Percent Saturation		**Wet Bulk Density (g/cc)**		**Dry Bulk Density (g/cc)**		**%Gas**	
Mean	97.1	Mean	1.44	Mean	0.73	Mean	2.13
Median	97	Median	1.44	Median	0.74	Median	2.21
Standard Deviation	1.3	Standard Deviation	0.02	Standard Deviation	0.02	Standard Deviation	0.95
Variance	1.7	Variance	0.00	Variance	0.00	Variance	0.91
Range	3.7	Range	0.05	Range	0.07	Range	2.74
Minimum	95.6	Minimum	1.42	Minimum	0.70	Minimum	0.53
Maximum	99.3	Maximum	1.47	Maximum	0.77	Maximum	3.27

Values for all Post- Shot Data GZ - 10 are based on grain densities originating from various methods of disaggregation at the Naval Research Laboratory

Naval Research Laboratory
Analysis of Geotechnical Data from Gently Disaggregated Tube Samples
Cores 10 Pre- and Post- Shot
BEAST Calibration Test
April 1995

Core 10 Pre- Shot

Tube #	Depth (cm)	Tube wt	Foil wt	Foil+tube+Sample wt	Total Dry Wt	wt of water	Water Content (%dry)
42	5	79.715	4.1	321.025	194.946	126.079	113.45
40	21	80.139	3.311	325.683	202.624	123.059	103.26
19	41	80.618	3.454	327.6	204.266	123.334	102.61
14	82	80.462	4.497	333.66	213.508	120.152	93.47
34	97	80.672	3.358	335.818	221.388	114.43	83.31
6	122	78.65	3.679	330.632	209.447	121.185	95.33

Tube #	Depth (cm)	Volume (g/cc)	Avg. Grain Density (g/cc)	Vol of Solids (cc)	Vol Voids (cc)	Void Ratio	Porosity (%)	Percent Satuartion	Wet Bulk Density (g/cc)	Dry Bulk Density (g/cc)	% Air
42	5	170.015	2.67	41.62	128.39	3.08	75.52	98.20	1.40	0.65	1.36
40	21	170.941	2.91	40.95	129.99	3.17	76.04	94.67	1.42	0.70	4.05
19	41	171.679	2.75	43.71	127.97	2.93	74.54	96.38	1.42	0.70	2.70
14	82	170.652	2.65	48.51	122.14	2.52	71.57	98.37	1.46	0.75	1.17
34	97	171.777	2.71	50.69	121.09	2.39	70.49	94.50	1.47	0.80	3.88
6	122	172.097	2.73	46.56	125.53	2.70	72.94	96.54	1.44	0.74	2.53

Core 10 Post- Shot

Tube #	Depth (cm)	Tube wt	Foil wt	Foil+tube+Sample wt	Total Dry Wt	wt of water	Water Content (%dry)
35	15	78.26	3.40	322.279	199.88	122.395	103.53
57	36	77.87	3.29	324.48	205.51	118.967	95.67
21	52	79.16	3.89	329.575	205.93	123.644	100.62
53	88	78.37	3.63	329.067	208.71	120.353	94.98
40	100	80.13	3.55	334.103	214.45	119.651	91.49
14	117	80.45	3.90	332.764	210.02	122.747	97.68

Tube #	Depth (cm)	Volume (g/cc)	Avg. Grain Density (g/cc)	Vol of Solids (cc)	Vol Voids (cc)	Void Ratio	Porosity (%)	Percent Satuartion	Wet Bulk Density (g/cc)	Dry Bulk Density (g/cc)	% Air
35	15	170.032	2.72	43.46	126.57	2.91	74.44	96.70	1.42	0.70	2.45
57	36	169.237	2.78	44.73	124.51	2.78	73.57	95.55	1.44	0.73	3.27
21	52	171.463	2.62	46.90	124.56	2.66	72.65	99.26	1.44	0.72	0.53
53	88	170.298	2.70	46.93	123.37	2.63	72.44	97.56	1.45	0.74	1.77
40	100	170.941	2.81	46.54	124.40	2.67	72.77	96.18	1.47	0.77	2.78
14	117	170.652	2.82	44.56	126.09	2.83	73.89	97.35	1.46	0.74	1.96

Mechanically Ground
Tube Data

Core 10 Pre- Shot	Tube	Depth (cm)	Avg Density (g/cc)	Volume (cc)	Vol of Solids (cc)	Vol Voids (cc)	Void Ratio	Porosity (%)	Percent Satuartion	Wet Bulk Density (g/cc)	Dry Bulk Density (g/cc)	% Air
	42	5	2.77	170.02	40.12	129.90	3.24	76.40	97.06	1.40	0.65	2.24
	19	41	2.70	171.68	44.52	127.16	2.86	74.07	96.99	1.42	0.70	2.23
	34	97	2.83	171.78	48.54	123.24	2.54	71.74	92.85	1.47	0.80	5.13
	6	122	2.94	172.10	43.24	128.86	2.98	74.88	94.04	1.44	0.74	4.46

Mechanically Ground
Tube Data

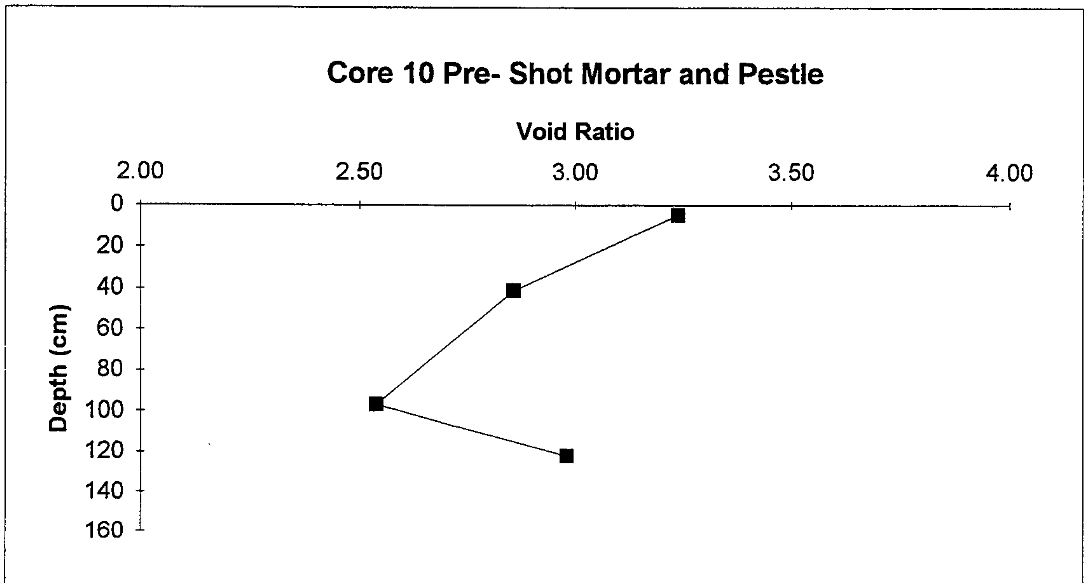
Core 10 Post- Shot	Tube	Depth (cm)	Avg. Density (g/cc)	Volume (cc)	Vol of Solids (cc)	Vol Voids (cc)	Void Ratio	Porosity (%)	Percent Satuartion	Wet Bulk Density (g/cc)	Dry Bulk Density (g/cc)	% Air
	35	15	2.87	170.03	41.19	128.84	3.13	75.77	95.00	1.42	0.70	3.79
	21	52	2.85	171.46	43.12	128.34	2.98	74.85	96.34	1.44	0.72	2.74
	53	88	2.74	170.30	46.25	124.05	2.68	72.84	97.02	1.45	0.74	2.17
	14	117	2.84	170.65	44.25	126.41	2.86	74.07	97.11	1.46	0.74	2.14

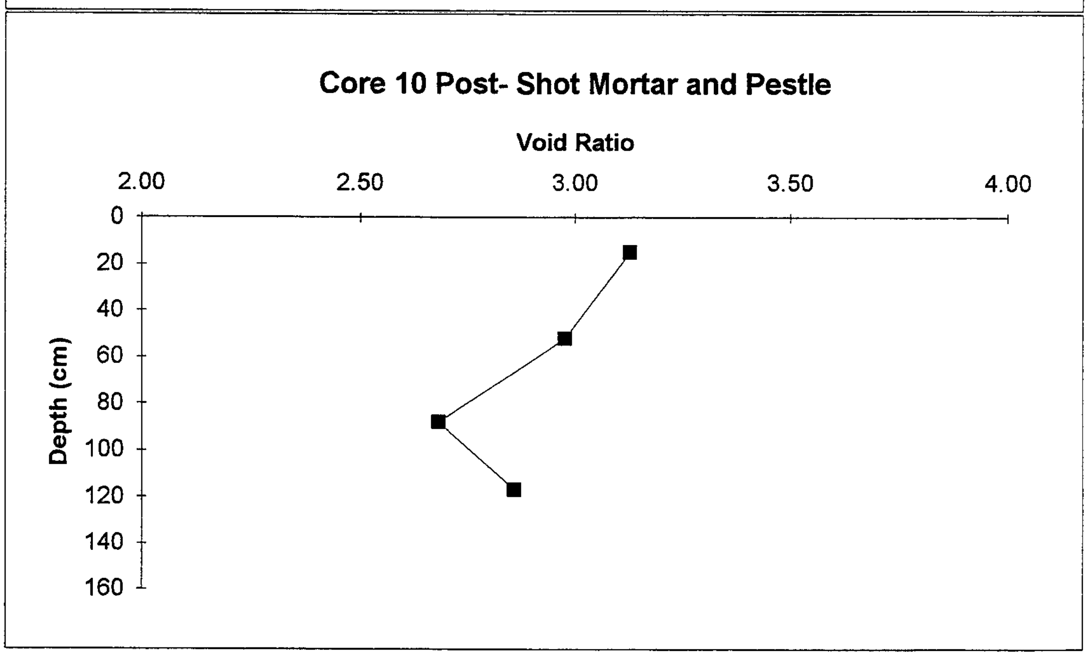
Geotechnical Data for GZ 10 Pre- and Post- Detonation.

Naval Research Laboratory
Statistical Analysis
of Geotechnical Data
Pre Detonation
BEAST Calibration Test
April 1995

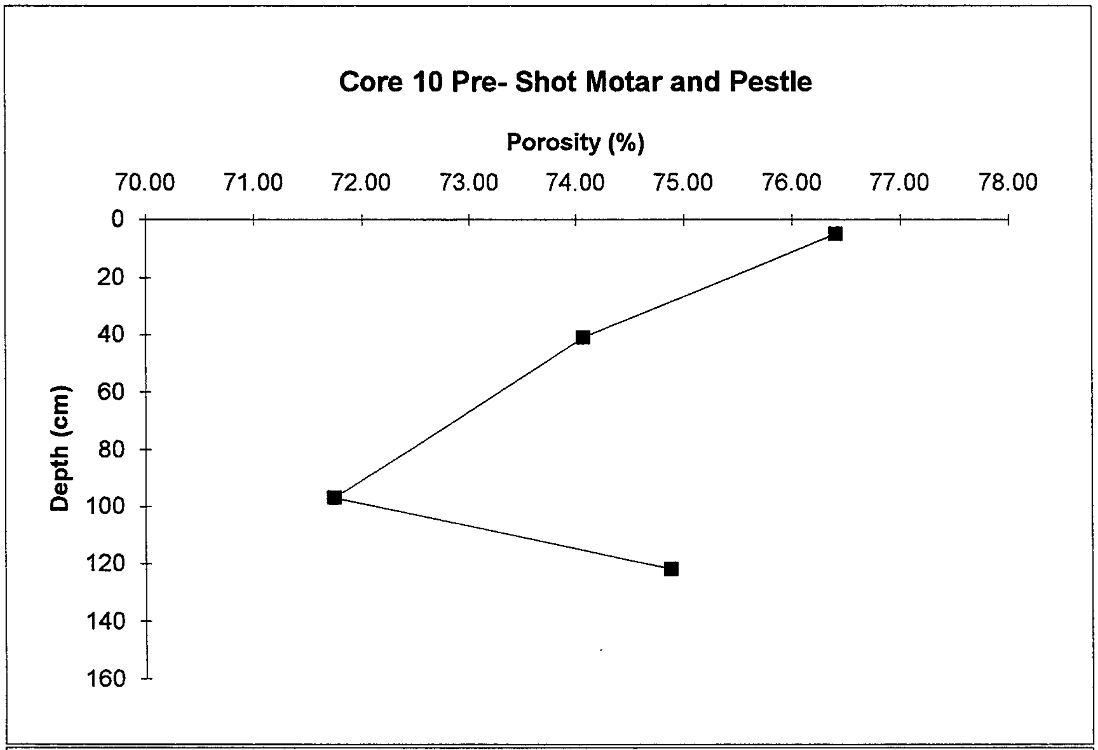
Vol of Solids (cc)		Vol Voids (cc)		Void Ratio		Porosity (%)	
Mean	45.34	Mean	125.85	Mean	2.80	Mean	73.5
Median	45.14	Median	126.75	Median	2.81	Median	73.7
Standard Deviation	3.89	Standard Deviation	3.59	Standard Deviation	0.32	Standard Deviation	2.2
Variance	15.17	Variance	12.92	Variance	0.10	Variance	4.9
Range	9.74	Range	8.90	Range	0.78	Range	5.6
Minimum	40.95	Minimum	121.09	Minimum	2.39	Minimum	70.5
Maximum	50.69	Maximum	129.99	Maximum	3.17	Maximum	76.0
Percent Saturation		**Wet Bulk Density (g/cc)**		**Dry Bulk Density (g/cc)**		**%Gas**	
Mean	96.4	Mean	1.43	Mean	0.72	Mean	2.61
Median	96.5	Median	1.43	Median	0.72	Median	2.61
Standard Deviation	1.7	Standard Deviation	0.03	Standard Deviation	0.05	Standard Deviation	1.21
Variance	2.8	Variance	0.00	Variance	0.00	Variance	1.47
Range	3.8	Range	0.07	Range	0.15	Range	2.89
Minimum	94.5	Minimum	1.40	Minimum	0.65	Minimum	1.17
Maximum	98.4	Maximum	1.47	Maximum	0.80	Maximum	4.05

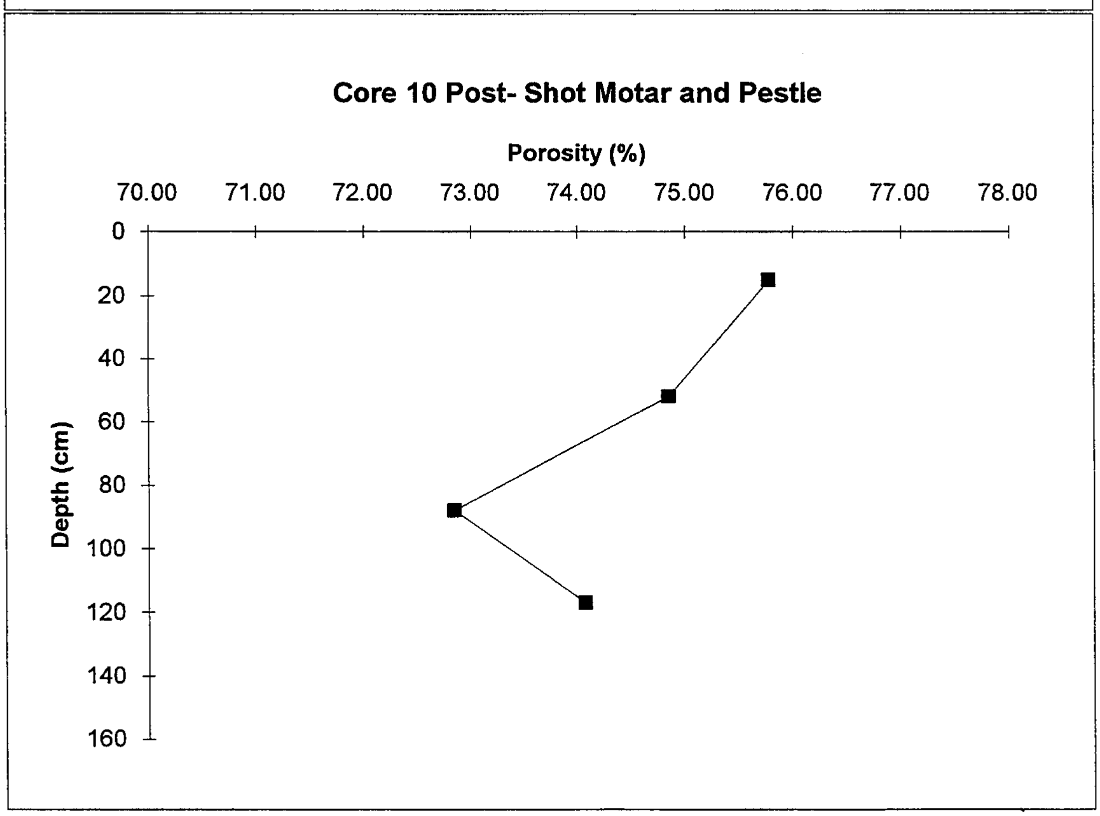
Values for all Pre- Shot Data GZ - 10 are based on grain densities originating from various methods of disaggregation at the Naval Research Laboratory



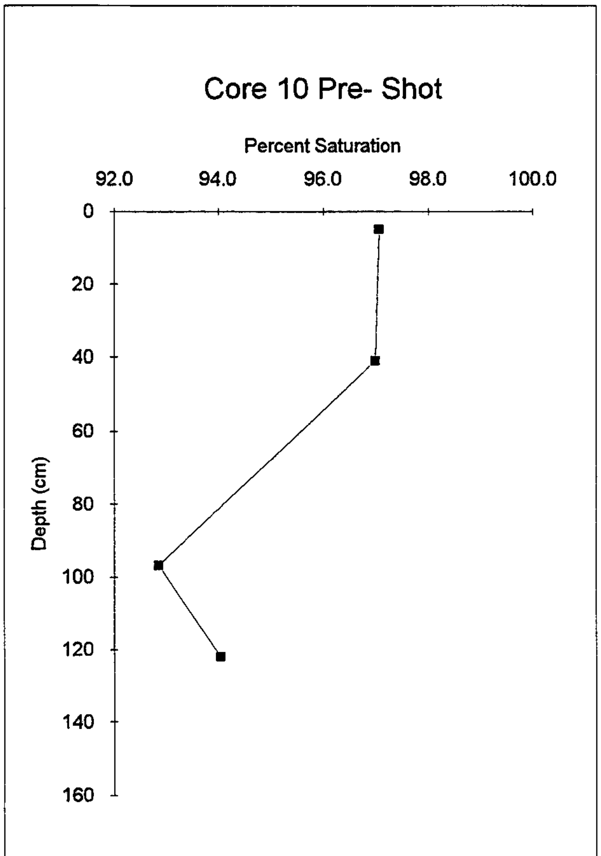


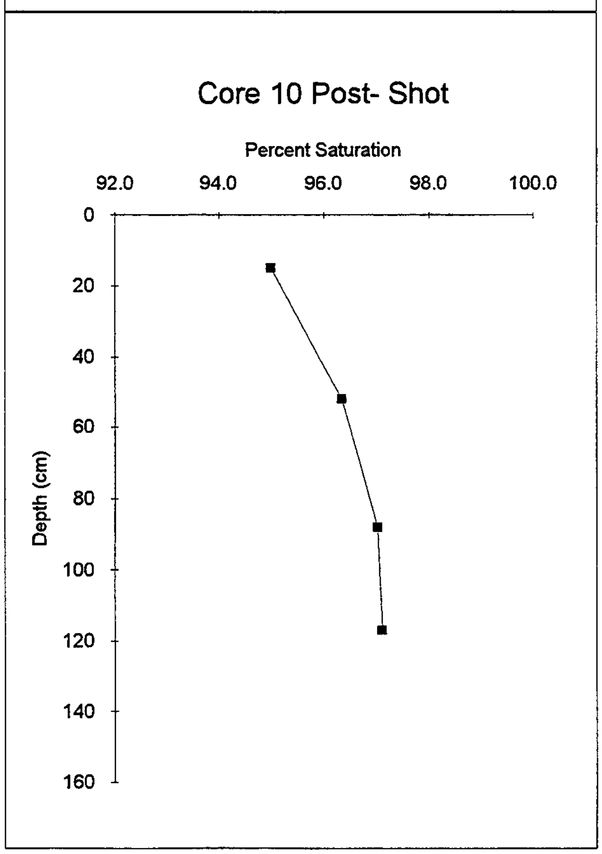
Plots of Void Ratio. Grain Densities from Sediments Ground with a Mortar and Pestle



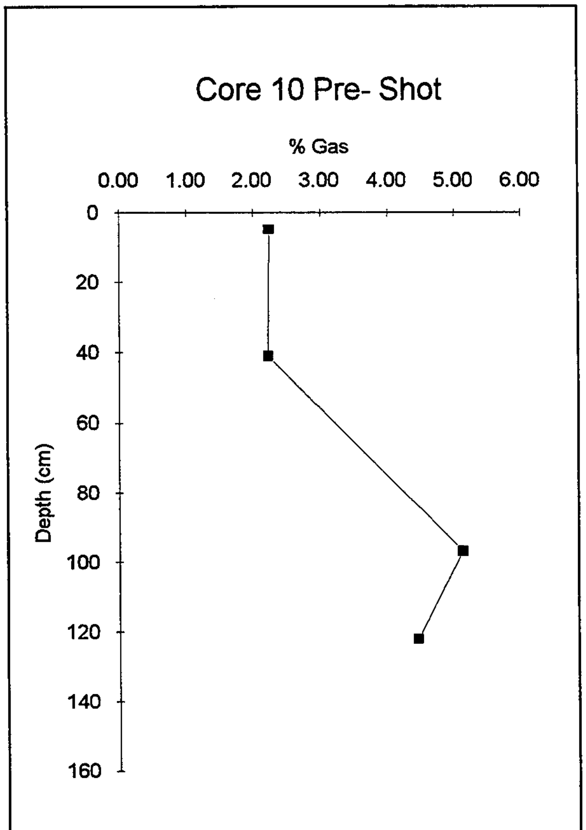


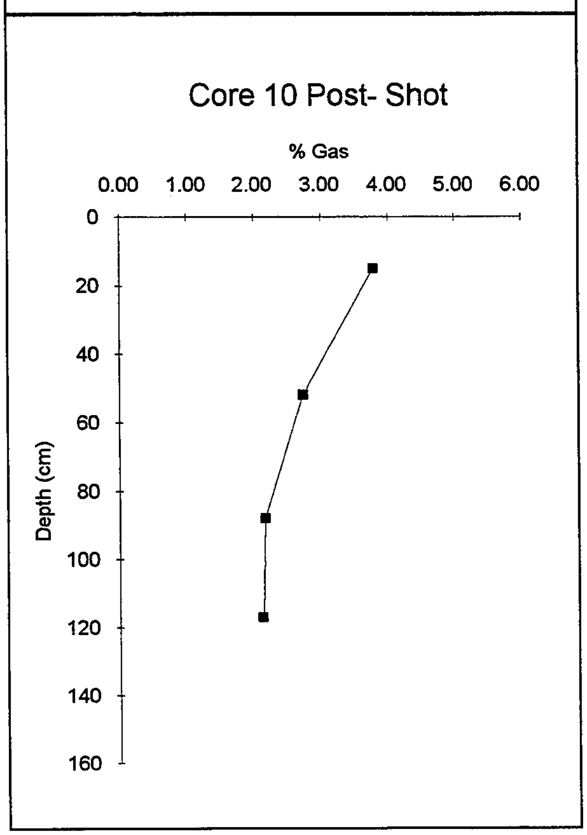
Plots of Porosity (%). Grain Densities from Sediments Ground with a Mortar and Pestle





Plots of Percent Saturation from Sediments Ground with a Mortar and Pestle





Plots % Gas Concentration for Mechanical Disaggregation.